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NEXT GENERATION MINE COUNTERMEASURES FOR THE VERY SHALLOW WATER ZONE IN SUPPORT OF AMPHIBIOUS OPERATIONS

by

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This report describes system engineering efforts exploring next generation mine countermeasure (MCM) systems to satisfy high priority capability gaps in the Very Shallow Water (VSW) zone in support of amphibious operations. A thorough exploration of the problem space was conducted, including stakeholder analysis, MCM threat analysis, and current and future MCM capability research. Solution-neutral requirements and functions were developed for a bounded next generation system. Several alternative architecture solutions were developed that included a critical evaluation that compared performance and cost. The resulting MCM system effectively removes the man from the minefield through employment of autonomous capability, reduces operator burden with sensor data fusion and processing, and provides a real-time communication for command and control (C2) support to reduce or eliminate post mission analysis.

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Further distribution of all or part of this report is authorized.

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ABSTRACT

This report describes system engineering efforts exploring next generation mine countermeasure (MCM) systems to satisfy high priority capability gaps in the Very Shallow Water (VSW) zone in support of amphibious operations. A thorough exploration of the problem space was conducted, including stakeholder analysis, MCM threat analysis, and current and future MCM capability research. Solution-neutral requirements and functions were developed for a bounded next generation system. Several alternative architecture solutions were developed that included a critical evaluation that compared performance and cost. The resulting MCM system effectively removes the man from the minefield through employment of autonomous capability, reduces operator burden with sensor data fusion and processing, and provides a real-time communication for command and control (C2) support to reduce or eliminate post mission analysis.

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EXECUTIVE SUMMARY

One of the responsibilities of the US Navy is to support and enable amphibious landings for the US Marine Corps. Prior to an amphibious landing, the path to the beach must be determined free of danger to the landing force. Often in areas of conflict, the path to the beach will be mined to prevent unobstructed access by an opposing force. If it is determined that sea mines may be in the Area of Operations (AO), mine countermeasure (MCM) operations are needed before the landing can take place. Current Marine Corps doctrine requires minefield clearance to occur within a 48 to 72 hour period in order to prepare the landing zones for an Amphibious Task Force (ATF). The US Navy's current MCM capability does not satisfy the Marine Corps amphibious doctrinal requirement. The MCM Detect-to-Engage (DTE) sequence consisting of search, detection, classification, identification and neutralization functions for current systems can take up to several weeks to complete. In order to ensure the safe approach and return of an ATF, there is a need to reduce the Detect-to-Engage mine clearance sequence in the 10-40ft depth range, while minimizing operational risk of mine clearance personnel to counter minefields.

In this capstone report, a thorough exploration of the problem space is conducted, including an MCM threat analysis, current and future MCM capabilities, and stakeholder research and interaction. Through research into current and future threat capabilities, it is realized that sea mines are becoming more challenging to search, detect, classify, identify, and neutralize. Enemy tactics of mine employment and technology increase the complexity of the problem; with targets now being made of sonar absorbing material, or developed to encourage vegetation growth in order to impede visual detection.

Investigation into current and future MCM systems capabilities indicate that systems must be able to conduct Port Defense, Sea Lane Protection and clearance in a non-permissive environment, to support MCM operations. This wide range of tasking requires a system to be flexible, expeditious, and accurate in locating, classifying, and identifying a target. Unmanned Underwater Vehicles (UUVs) or Autonomous Underwater Vehicles (AUVs) are identified as current and future system solutions that provide an advantage to detect, classify, and identify the threat with powerful sensor suites in comparison to diver and Marine Mammal Systems (MMS). UUV systems have the ability to launch and perform MCM operations more covertly than diver and MMS systems, but require more time for data analysis, and their size requires launch from surface craft or helicopter platforms. Although UUV technology is showing promise to solve the challenges for MCM operations, the impact this complex technology brings to the MCM community and the Navy needs to be evaluated on a continuing basis.

Current MCM-1 ships are being phased out and Littoral Combat Ship (LCS) platforms are being built as replacements to support MCM missions. However, MCM will not be the sole mission of LCS platforms, as the LCS class is being developed to support multiple mission criteria in order to meet the future needs of Navy. This drives concerns for future MCM Concept of Operations (CONOPS) and mission tasking due not only to the requirement to reduce the MCM footprint, but also to reduce manpower requirements.

In order to address the capability gaps discovered, a set of solution neutral requirements were developed as part of the analysis of current capabilities and stakeholder needs. System functions were then developed based on the requirements that were generated to further define the system. Once the solution neutral system was defined, it was necessary to set system boundaries in order to scope the project's effort towards a manageable solution with respect to time and resource availability. The system boundary was reduced to search, detect, classify, identify, engage and communications functions related to the MCM system, system operators, and host platform. The full engage function was later determined to be too complex for our scope of research, and it is recommended to be covered by another research cohort.

Investigation of potential solutions to fit the requirements lead to the elimination of airborne and surface based systems as they would not be able to covertly conduct operations. Based on research and MCM roadmap doctrine, current capability gaps were mapped to potential solutions for removing the man and mammal from the mine field, reducing post mission analysis, and establishment of real-time communications. Three alternative architectures were developed to support reduction of the DTE sequence and to address the overarching capability gaps. Within each architecture solution, system components were mapped to identified functions and requirements to ensure that the MCM system needs were met. Each of the architectures was developed with a specific concept of operations that fully detailed the real-time communication network and system employment solution.

Each of the three architecture solutions were compared using modeling and simulation software tools that represented each system in two separate minefield design reference missions. Performance of each alternative was analyzed and compared based on identified measures of effectiveness.

The total cost of ownership for each of the architectures was developed using current baseline system costing information and government costing sites. All three architectures were then evaluated in an analysis of alternatives that combined an evaluation of the cost estimates with previous system performance results to determine a system solution recommendation.

The problems and capability gaps defined in MCM operations are complex with many challenges that exist today and in the future. As manning requirements are being reduced across the Navy, the need for future systems to remove human dependency will be increasing. The final results of our analysis shows that a fully autonomous system can reduce human burden for target processing and remove both man and mammal from the minefield. In order to support the employment of autonomous systems, it is necessary that real-time communication networks are established not only to support autonomous operations but also to reduce or eliminate post mission analysis from the DTE time line.

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I. INTRODUCTION

A. BACKGROUND

One of the responsibilities of the US Navy is to support and enable amphibious landings for the US Marine Corps. Prior to an amphibious landing, the path to the beach must be determined free of danger to the landing force. Often in areas of conflict, the path to the beach will be mined to prevent unobstructed access by an opposing force. If sea mines are determined to be in the path of the landing force, mine countermeasure (MCM) operations are needed before the landing can take place.

Historically, the US Navy's mine countermeasures have been represented by a triad of systems consisting of dedicated surface platforms (e.g., Mine Countermeasures MCM-1 class ships), aviation platforms (e.g., MH-53E Sea Dragon helicopter), and subsurface detachments with Explosive Ordinance Disposal (EOD) divers and Marine Mammals Systems (MMS) that conduct mine hunting and mine sweeping missions (PEO LMW, 2009). Current mine countermeasure ability to support amphibious landings is sufficient for deep water, however, a gap lies in clearing the VSW zone, where in contested water, all three elements of the traditional triad are challenged (NWP 3-15, 1996).

The VSW zone, defined as depths between 10 to 40 feet of water, exhibits unique environmental characteristics to Underwater Mine Countermeasures (UMCM) that are not as easily overcome as in other operational depth areas. Underwater visibility is very limited; murky sea floors contribute to turbid underwater environments with low light conditions at depth, making it difficult for divers to operate, even during daylight. These environmental aspects are compounded by the confined nature of the VSW zone; consisting of inlets, berthing areas, dock and bridge pillars, and confined channels that only increase the DTE timeline by significantly limiting mobility (NWP 3-15, 1996). Performing mine countermeasure activities in contested VSW zones to support pre-assault, advance force exploration, and reconnaissance amphibious landing missions, with brisk engagement requirements, presents restrictions in rapidly detecting and clearing mines without being detected by adversaries prior to amphibious force engagement. Mine detection in contested waters close to shore allows for easy detection of traditional surface (Surface Mine Counter Measures; SMCM) and aerial (Airborne Mine Counter Measures; AMCM) platforms by unfriendly radars and simple visual scans.

While much of the United States' mine countermeasure missions are performed utilizing aerial and surface platforms, alternative methods are being utilized to address the 10-40 foot region requirements. Unmanned Underwater Vehicles (UUVs) with specialized sensors,

navigation, communications, propulsion, and power subsystems are being tested and fielded to conduct localization searches aimed at reducing the tactical timeline for search operations (PEO LMW, 2009). Employment of UUVs is an attempt to limit or completely avoid exposure of divers to explosive hazards, and other hazards of the operational environment during the precursory step of detecting, localizing, and gaining access to threat objects.

Man-portable class UUV systems have been employed by the Navy for the past several years (PEO LMW, 2009). While small UUV systems are a relatively new concept for the Navy, they have been received with much enthusiasm as an initial step in getting the man out of the minefield. Strides have been made in the development of these new concepts, but a great deal of work is still needed to fulfill the full set of requirements from the Fleet (PEO LMW, 2009).

Although the man-portable UUVs in service today address many of the basic UMCM capability needs, they are not a panacea for addressing the full range of tasks in the diverse underwater environment. UMCM systems degrade in performance capability in more complex seabed environments where burial, high clutter and irregular bottom types are at play (NWP 3-15, 1996).

B. PROBLEM STATEMENT

Current naval mine search, detection, classification, and neutralization systems can take up to several weeks to complete mine clearance operations. This current capability is not consistent with the Marine Corps amphibious doctrinal requirement of several days. In order to ensure the safe approach and return of an Amphibious Landing Force, there is a need to reduce the DTE mine clearance sequence in the 10-40ft (VSW zone) depth range while minimizing operational risk of mine clearance personnel to counter minefields.

C. RESEARCH QUESTIONS

This Capstone Project is interested in researching and providing alternative and employable system solutions to reduce the DTE mine clearance sequence in the VSW zone through investigating the answers to the following research questions:

1. Is it possible to completely remove the man/mammal from the minefield during UMCM operations?
2. Is it possible to have a system or system of systems that can detect and clear a minefield path for amphibious landings within the required CONOPS time specifications?
3. Will the MCM solutions present today or planned in the near future be able to handle current and future threats?
4. What is the greatest obstacle in reducing the DTE sequence timing?

5. What alternatives exist to overcome obstacles to reducing the DTE sequence timing?
6. For an implemented solution, what are the risks and benefits?

D. ASSUMPTIONS

In the execution of this Capstone Research Project, assumptions were made to allow for detailed analysis of specific areas of the problem space taking into account the allotted project time and the individual knowledge, skills, and capabilities of team members. Throughout the project, the following high level assumptions were made:

- Current enemy tactics are still consistent with previous engagements from past battles or encounters.
- Emerging mine technology is consistent with US or allied capabilities.
- The VSW region will be typically a 500 yard by 500 yard region of the boat lane.
- The enemy threat who has planted mines for an anti-landing defense will actively survey the mined area from a distance and will engage the MCM force upon detection with direct and indirect fire.
- The design reference mission (DRM) will have both visual and electronic oversight to detect any MCM or opposing force movement.
- System concept design solutions will only be developed for manpower and equipment within the project defined system boundary.

In addition to the high level assumptions, more detailed assumptions were implemented in the individual analyses in this report and are detailed further in the specific report sections. Additionally, for the threat and current capabilities analyses, the data comparing the systems use estimated values from unclassified information and are in most cases approximations.

E. SYSTEMS ENGINEERING PROCESS

Figure 1 presents the tailored Systems Engineering Process used through this Capstone Project. The major phases of the Systems Engineering Process consisted of the Problem Exploration Phase, the System Definition Phase, and the Modeling of Alternative Architecture Phase. Guided by the defined System Engineering Process, the capstone team members were able to successfully define and scope the Capstone Problem, conduct research into the problem area, develop functional requirements, and assess the implementation qualities of architectural solutions. The following sections describe the individual parts of the Systems Engineering Process in detail.

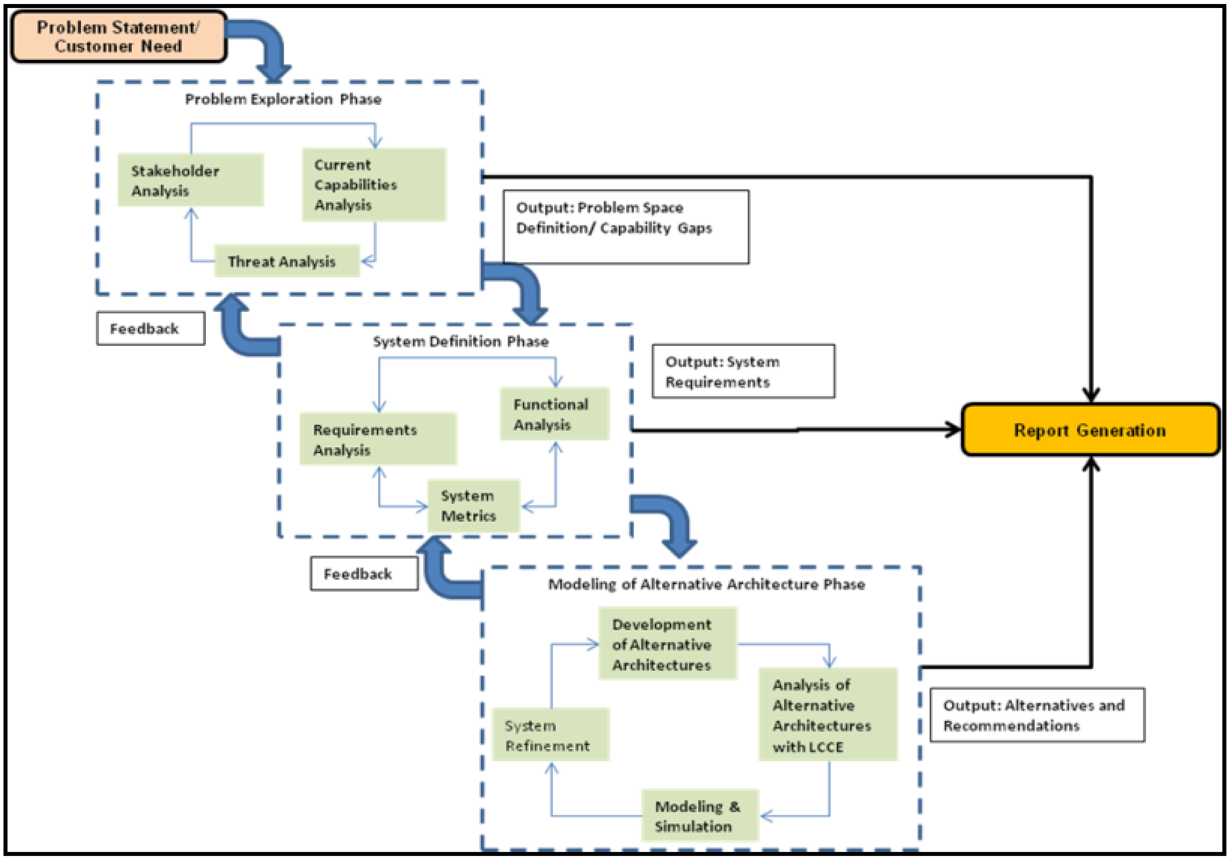

Figure 1. Capstone Project System Engineering Process

The tailored System Engineering Process developed by the Advanced MCM System cohort team was used as guidance for executing the Capstone Project.

1. Problem Statement/Customer Need

The Systems Engineering Process started with the definition of a known capability gap related to one team member's command. Once the capability gap was agreed to, the problem statement was scoped to a level of work deemed to be achievable in the given project timeframe.

2. Problem Exploration Phase

With the problem statement scoped, the problem exploration phase was entered. This phase consisted of conducting research to further define the problem space. The Problem Exploration Phase consisted of three activities: stakeholder analysis, threat analysis, and current capabilities analysis. A comparison of the three activities resulted in identifying capability gaps related to the defined problem space and was used as the entrance criteria for starting the system definition phase.

a. *Stakeholder Analysis*

The stakeholder analysis began with the problem statement being leveraged to define a list of stakeholders and a summary relationship between MCM and amphibious landings. Research was then conducted using MCM documentation and doctrine to generate questions for stakeholders to gain more insight into the problem space. Identified stakeholders were interviewed and asked to identify their interests, potential loss in the defined problem, or any significant requirements related to the problem statement. This resulted in a list of stakeholders' needs that was fed into both the current capabilities analysis and the threat analysis for consideration. The outputs of both the threat and capabilities analyses were fed back into the stakeholder analysis identifying new stakeholders and additional questions to pose to stakeholders. The stakeholder analysis facilitated interaction between stakeholders in soliciting input guidance toward developing solution architectures.

b. *Current Capabilities Analysis*

The current capabilities analysis consisted of a thorough study of all existing technologies and systems currently fielded for MCM in the VSW zone. The analysis looked at US Navy systems that were deployed or planned to be deployed in the near future, and included applicable allied MCM capabilities. Through research of current doctrine, approved development programs, and stakeholder interviews, the current capability analysis identified how existing and planned platforms fulfill stakeholder needs. However, the current capability analysis also identified capability gaps that cannot be met with existing or planned platforms using current policy, procedures, and tactics. The findings of the current capabilities analysis fed back into the stakeholder analysis for further interaction with stakeholders in investigating gaps and current/future systems.

c. *Threat Analysis*

The threat analysis identified current mine technologies employed by opposing forces. Specific characteristics of each threat were detailed along with the methods and tactics used in deploying each mine type in the VSW zone. The threat analysis defined the mines that were of greatest concern in the VSW zone because of their payload size and of their detection rate utilizing current MCM assets. The threat analysis fed into the stakeholder analysis in order to confirm the findings with stakeholder representatives.

3. System Definition Phase

The System Definition Phase began with inputting the outputs from the Problem Exploration Phase, namely the stakeholder, capabilities, and threat analyses. The System Definition Phase consisted of a requirements analysis, functional analysis, and system metrics

development. The outputs of the system definition phase: requirements, functions, and metrics served as inputs to the Modeling of Alternative Architectures Phase.

a. Requirements Analysis

The requirements analysis utilized the results of the stakeholder, capabilities, and threat analyses to evaluate mission and operational environments. From the construction of a theoretical operational environment, a list of stakeholder needs and constraints were developed pertaining to the problem space. Details of capability gaps and stakeholder inputs were used to develop system requirements necessary to accomplish the MCM mission given the constraints. Information from the functional analysis process and the metrics refinement fed back into the requirements analysis for mitigation when requirements were discovered to be inconsistent or missing at these later stages.

b. Functional Analysis

The functional analysis further developed system operation details, functions, and tasking. Decomposition of requirements from the requirements analysis identified lower-level functions and resulted in the refined functional description of the system. The functional analysis resulted in a functional architecture developed in Vitech Corporation’s CORE software. After the functional architecture was in CORE, requirements were mapped to functions to ensure traceability from top level to lower level functions and requirements. The mapping of functions to requirements in CORE resulted in adding more details to requirements and functions where needed, and served as the input into the system metrics definition.

c. System Metrics

The System Metrics development took previous work to develop top level system metrics. Once system metrics were developed, they were compared to the requirements to ensure applicability and traceability. The development of system metrics resulted in the conclusion of the System Definition Phase, with the requirements, functions, and metrics being fed into the Modeling of Alternative Architectures Phase to further develop the system architecture and compare possible solution types.

4. Modeling of Alternative Architectures Phase

The Modeling of Alternative Architectures Phase began with the outputs from the System Definition Phase. Our team used Vitech Corporation’s CORE software, Microsoft’s Excel software and *Imagine That*’s ExtendSIM modeling software to determine which alternative architecture performed the best. The analysis conducted during this phase occurred through an iterative process between the three phases that resulted in a solution definition and recommendation. The output of this phase was a combination of the Development of Alternative

Architectures, Modeling and Simulation, and System Refinement steps in the form of an Analysis of Alternatives with Life Cycle Cost Estimation (LCCE).

a. Development of Alternative Architectures

This step took the outputs from the System Definition Phase to develop a list of Alternative Architectures. The top level problem statement of DTE reduction was mapped to capability gaps and analyzed for solutions to reduce or close the gaps. Capability gap solutions were translated to component solutions and recommendations for three Alternative Architectures. These Alternative Architectures were then used as input to the Modeling of Alternative Architectures Phase. As the Modeling of Alternative Architectures Phase developed feedback to the System Definition Phase, the lists of Alternative Architectures were modified.

b. Modeling and Simulation

Modeling and Simulation was used as a verification and validation tool of the system architecture and requirements of the system solution. Models were created for each of the system architectures and compared with system metrics to determine if the system is viable, and how well the technical performance of the proposed system compares to the other systems that were developed in the Analysis of Alternatives. The output of Modeling and Simulation was used as the input to the System Refinement stage to provide technical performance information used to eliminate or promote specific design approaches.

c. System Refinement

System refinement was performed to review system solution details to select and validate the best solution. Both simulation and life-cycle cost results were used in determining the final recommendations for the next generation MCM system.

d. Analysis of Alternative Architectures with LCCE

The Analysis of Alternative Architectures was conducted based on inputs from the System Definition phase. The System solutions were compared based on the alternative architectures for technical and cost parameters. Performance metrics from Metrics Refinement represented criteria for comparing system solutions. The output of this step was a cost benefit analysis and an analysis of alternative architectures. The results of the Modeling and Simulation step were used to further refine the architecture alternatives.

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II. PROBLEM EXPLORATION

A. THREAT ANALYSIS

Mines in the VSW zone are of major concern to the US and its allies. This threat analysis was limited to those mines expected to be found in the VSW range with the ability to hinder the advancement of US troops during an amphibious landing on foreign soil.

Naval mines are inexpensive to produce and can be deployed rather quickly. With this in mind, they are seen as an easy way of denying free access to the coastline by an amphibious force (PEO LMW, 2009; NWP 3-15, 1996). Mines can be used effectively to limit the points of entry for an assault force, as a force multiplier by limiting the enemy's ability to maneuver, or to allow friendly forces time to maneuver. A minefield can have both offensive and defensive objectives. Offensive minefields are placed to slow the advancement or prevent movement of the enemy. This could include placing mines in the port or sea lanes of an enemy. Defensive minefields are intended to protect coastline from assault (JP 3-15, 2011).

A major advantage of using mines is the psychological affect that they have on the opposition (PEO LMW, 2009; NWP 3-15, 1996). As witnessed in Desert Storm, a minefield may contain dummy or faulty mines and still prevent access since the potential loss of personnel and equipment is too great to risk entering the minefield (Final Report to Congress: Conduct of the Persian Gulf War, 1992). From this it can be concluded, that even if the mine is inoperable it still serves a purpose.

The main types of mines that may be found in the VSW zone, the methods for triggering them, and the methods used for deploying a minefield are described in this threats analysis section. The technology being incorporated into current and future mines has been examined. Finally, the most likely aggressors and their current mine warfare capabilities have been detailed.

1. Mines Analyzed

Due to variation in mine size and functionality, an overall "blanket" approach to identifying, classifying, and mapping each mine within a similar zone of interest is not practical. The following types of mines are likely to be encountered in the VSW range during an amphibious landing in a foreign country: moored, bottom, and drifting (Carson-Jelley, 2011). In order to distinguish among the variety of mines, a number of factors were considered when it came to identifying mines of concern. Chief among them was locality. The primary focus is the 10-40ft depth range and, therefore, the use of some mine-types is impractical. Typically, factors such as obsolescence and redundancy were also taken into account; however, it is important to

remember that the primary goal of a mine is to slow or stop the advancement of the opposition. As long as it is believed that the mine poses a threat, obsolete or otherwise, it is serving its purpose as a deterrent.

Figure 2 illustrates the various types of mines and the positions that they may take in an ocean minefield (note that Figure 2 is not to scale). The VSW section depicts three different mines: drifting (floating), bottom, and moored.

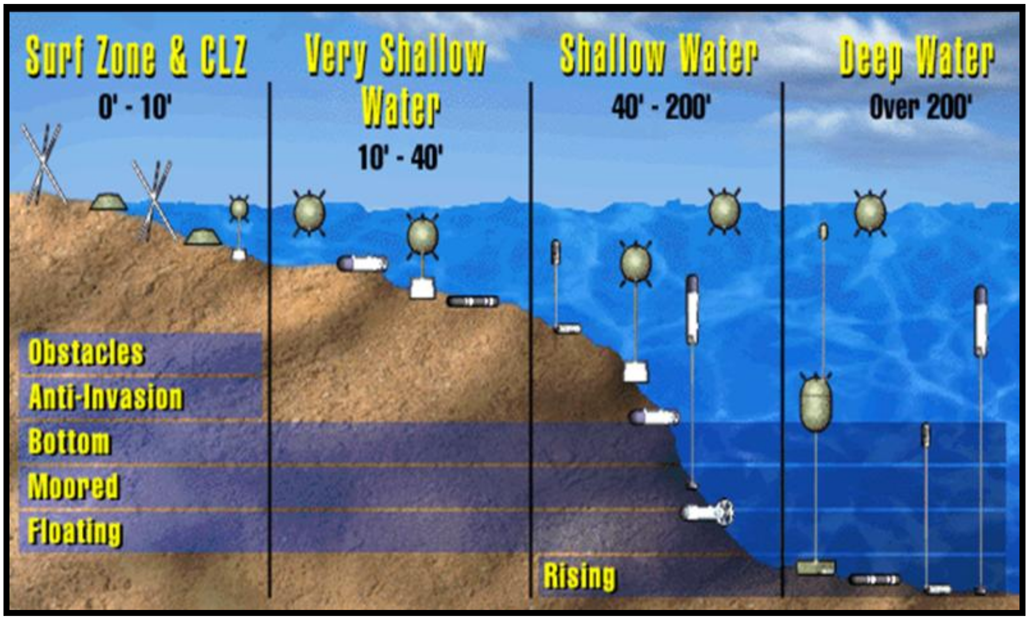

Figure 2. Mines Used by Depth Range

Depiction of mine type allocation related to ocean depth zones. This project is concerned with the VSW zone containing threats of bottom, moored, and floating/drifting mines (Carson-Jelley, 2011).

a. Bottom Mines

Bottom mines are powerful, non-buoyant mines that are planted on the sea bottom and held in position by their weight. Additionally, they can be referred to as "buried mines," in which case they are embedded in the sea floor, or "proud mines," when they remain uncovered. Figure 3 shows a Manta mine which, over time, has been partially buried by wave action. Since the mine case is non-buoyant, there is a larger capacity for explosives, making the damage radius much larger than that of the moored mine. If the mine is intended for a surface ship, it is best that it be positioned no deeper than 200ft below the water's surface. At the 10-40ft depth, bottom mines are within their effective range and could be triggered by both magnetic and seismic triggers (NWP 3-15, 1996).

1996).

Figure 3. Bottom Mine

Image of a bottom Manta type mine, which has been partially buried by the ocean bottom due to wave action over time. Bottom mines contain a larger capacity for explosives since they are non-buoyant and their whole casing can be filled with explosives instead of air to permit buoyancy (Sei Spa, 2011).

One variation on the bottom mine is the propelled bottom mine. This variation is equipped with a propulsion system that is intended to position the mine at a specified location. This can be useful when laying mines, since a ship can fire the bottom mine and its propulsion system would then guide it to its final plant position before arming itself (NWP 3-15, 1996).

Bottom mines are the most difficult to detect. The latest counter-countermeasure technologies employ features such as various mine shapes to encourage burial or deflect sonar signals to reduce the effectiveness of search equipment. In some cases, bottom mines are constructed with fiberglass and special sound-absorbing materials which further reduce the signal returned by sonar. Any clutter existing on the ocean floor (i.e., natural formations, discarded items, etc.) increases environmental complexity and makes it more difficult to detect a bottom mine. This is compounded by the fact that some mines are manufactured to have the appearance of a discarded object, in hopes of reducing its detection (Rabiroff, 2011). Due to their large damage radius and the difficulty in detecting them, bottom mines are considered the greatest threat in the VSW zone. Because of this, bottom mines are the most commonly produced and utilized mine for non-NATO countries, specifically China and Iran (NWP 3-15, 1996).

b. Moored Mines

Moored mines have a positively buoyant casing which is moored to an anchor on the sea bed via a chain or cable as seen in Figure 4. This allows them to float at a predefined depth which is dependent upon the length of the cable, the weight of the cable, and the case's crush depth. Since the mine casing is designed to be buoyant, there is less space to house the explosives. Because of this, moored mines are less powerful and have a smaller radius of damage than that of a bottom mine. A major benefit, however, is that they utilize a host of triggering methods including proximity, acoustic, magnetic, optical shadowing, and pressure sensors. Over time, it is possible that a moored mine may separate from its anchor and float to the surface; these are known as floaters. In some cases, the mine is fitted with a self-destruct mechanism that will flood the casing with water in the event that the mine is separated from its mooring. Provided that this does not occur, a moored mine can have a lifespan exceeding 10 years (NWP 3-15, 1996).

Moored mines can also be tethered together to create what are called "daisy-chained" mines. These consist of two moored mines that are tied together about 60 feet apart and float a few meters below the surface. When the target hits the cable, the warheads are drawn down either side of the ship's hull, exploding on contact (NWP 3-15, 1996).

Moored mines are vulnerable to a catenary sweep, wherein one or two ships drag a wire, or net catenary, to scoop up mines. The mine, vulnerable to being mechanically severed from its mooring cable, would then initiate its self-destruct sequence whereby the mine is flooded. Then, depending upon the type of fuse utilized, the mine can be detected and detonated via acoustic sweeps, electromagnetic sweeps, or pressure detonation, making it effectively neutralized.

Figure 4. Moored Mine

MCM EOD Divers neutralizing moored mine. Moored mines have a positively buoyant casing which is moored to an anchor on the sea bed via a chain or cable as seen in the figure. Since the mine casing is designed to be buoyant, there is less space to house the explosives making moored mines less powerful than non-buoyant mines (Sea Mines: An Explosive Problem, 2009).

c. Drifting Mines

Drifting mines consist of a buoyant case allowing them to float at or below the water's surface without anything to fix them in one position. As a result, they are free to drift with the current and shifting tides as shown in Figure 5. Some drifting mines can be modified by fixing them with a weight or impeller that will keep them near the sea bottom; these are known as "creeping mines" due to the fact that they drift along the ocean floor. The Piao-3, utilized by China, is one such mine. This mine uses impellers which allow the mines to hover at a constant depth (Erickson, Murray, & Goldstein, 2007).

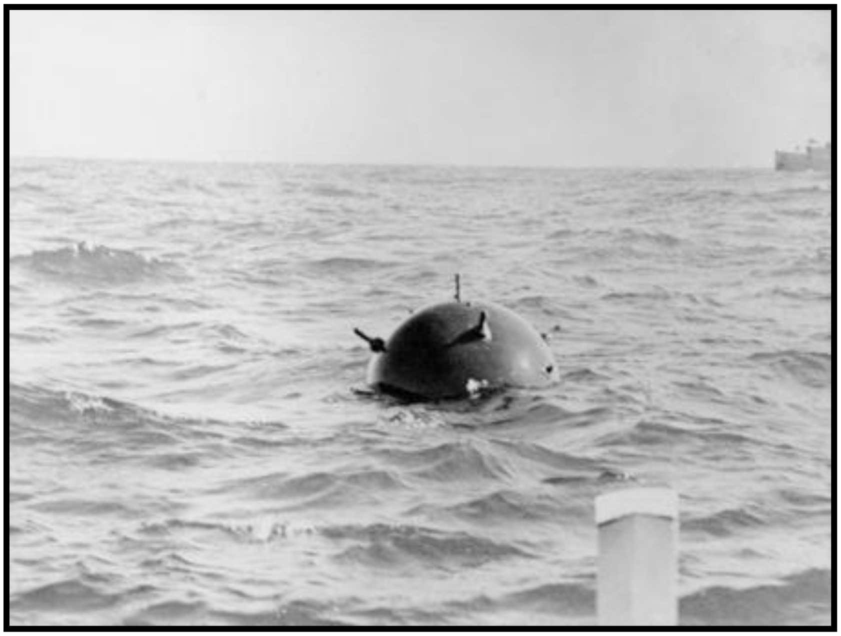

Figure 5. Drifting Mine

Drifting mines consist of a buoyant case allowing them to float at or below the water's surface without anything to fix them in one position. As a result, they are free to drift with the current and shifting tides (German Mine).

One advantage of drifting mines is that they can be set to hover around a specific depth, which is a great benefit when mines are distributed in waters that are too deep for moored or bottom mines. Additionally, it is difficult for the opposition to map the minefield since the mine's position is not static. Drifting mines are less likely to remain in a specified area for an extended period of time. Drifting mines are also easily deployed, unlike moored and bottom mines, making them an extremely valuable asset for countering an amphibious assault (Korean People's Army Navy, 2011). Furthermore, drifting mines are typically more simplistic, utilizing older technology than bottom and moored mines, making them less expensive.

The disadvantage of drifting mines is that their position is ever-changing and they endanger friendly ships as well as enemy ships (NWP 3-15, 1996). According to The Hague VIII Convention of 1907, automatic contact mines that are not under the control of the person who laid them must become inactive within 1 hour (Laws of War: Laying of Automatic Submarine Contact Mines, 1907). Because of this, drifting mines are usually fitted with a self-destruct mechanism that will sink them after a given period of time, neutralizing any threat they may cause. Regardless, the use of drifting mines is not within the rules of engagement, and they are considered illegal warfare due to the danger they pose to commercial and civilian surface ships (NWP 3-15, 1996).

2. Primary Mine of Concern

From the analysis performed on the three main types of mines it can be determined that the bottom mine is the greatest threat to an amphibious assault in the VSW range. The primary reasons being the bottom mine's larger capacity for explosives and its ability to be hidden in ground clutter. With only the VSW range in mind, any craft will be in the damage radius of any mine placed in this region. However, the moored and drifting mines have a smaller explosive payload capability, comparatively speaking, and the damage caused by these mines is not as great when detonated at an equal distance. When mine hunting and sweeping techniques are considered, moored mines are easier to detect, or mechanically sweep. Discussions with stakeholders indicate that drifting mines can be difficult to detect, are easily deployed, and their movements make them difficult to track. However, due to the possibility of moving out of the VSW range or deactivating after a set period of time, this analysis does not consider them to be a threat greater than bottom mines.

Table 1 is a summary of the general characteristics of the three types of mines considered in this analysis. This summary was developed from information gathered from many sources (Erickson, Goldstein, & Murray, 2009; NWP 3-15, 1996; Mason, 2009; Molina, Sánchez, & Rodrigo, 2007; Sei Spa, 2011; Rios, 2005).

Table 1. Mine Characteristics

Summary of the general characteristics of the three types of mines present in the VSW depth zone: bottom, moored, and drifting mines. The table was compiled from information gathered from many sources (Erickson, Goldstein, & Murray, 2009; NWP 3-15, 1996; Mason, 2009; Molina, Sánchez, & Rodrigo, 2007; Sei Spa, 2011; Rios, 2005).

Mine	Mass	Dimensions	Depth	Tethering Mechanisms	Lifespan
Moored	Around 440lbs, including 175lbs of explosives	Varied. Some are around 22in by 115in	The max water depth is limited by the length of the mooring cable, the weight of the cable, and the mine case crush depth	Varied. Typically a steel cable or chain connects the mine to an anchor.	> 10 years. Fitted with a self-destruct device that will cause them to flood and sink if they are separated from their anchor
Bottom	Around 330 to 3,300lbs, including about 275 to 3,090lbs of explosives	Varied. Some are around 19in by 128in and 29in by 161in	Used when water is no more than 200ft deep, unless mining applied for submarines around 660ft deep	Non-buoyant casing causes the mine to sink to the sea bed. No tether, held in place by weight.	
Drifting	Around 440lbs, including 180lbs of explosives	Varied.	Surface or the buoyancy can be adjusted so that the mine floats at a preset depth. Good for areas that are too deep for moored or bottom mines.	No tether.	Drifters are usually fitted with devices designed to sink them after a relatively short life span

3. Triggering Mechanisms

According to Mine Warfare (NWP 3-15, 1996), the various types of triggering mechanisms can be grouped into three categories: "contact actuation," "influence actuation," and "command and control actuation." The mines described thus far are equipped with one or more of these types of triggering mechanisms in order to resist minesweeping tactics (NWP 3-15, 1996). Each mine contains a firing mechanism which triggers the actuation once it receives an electrical signal from its detector. Once the firing mechanism receives the signal, it is analyzed to determine if it came from a valid source, such as an enemy ship. The firing mechanism will initiate detonation of the mine if the signal source is deemed valid and within range.

a. Contact Actuation

The contact trigger is one of the oldest and easiest to use. In order to detonate the mine, the watercraft must make physical contact with the mine. Current mine warfare tactics describe many different types of switches that can be used. What is common to all the switches is that once the watercraft makes contact with the mine an electrical connection is made and causes detonation (NWP 3-15, 1996).

During Desert Storm, the Iraqis made significant use of moored mines using a contact actuation method. Some examples of these are the Soviet M-08, and the Iraqi-produced LUGM-145 (Final Report to Congress: Conduct of the Persian Gulf War, 1992).

Since this analysis is limited to the 10-40ft depth range, the types of mines most likely to have this type of triggering method are either moored mines or drifting mines. Although bottom mines can also have this type of triggering method, this analysis assumes that watercraft transiting the 10-40ft depth range would not commonly contact the sea floor making this triggering method ineffective for bottom mines.

b. Influence Actuation

The influence actuation trigger type does not require physical contact between the ship and the mine. As a ship or other craft moves through the water, there are a multitude of signals that can be detected. This makes it possible to have the mine further away from the target ship and still trigger a detonation. The influence triggers can be grouped into four different sub types. According to Mine Warfare (NWP 3-15, 1996), these can be listed as "acoustic influence," "electromagnetic influence," "pressure influence," and "seismic influence."

Acoustic

Acoustic influence triggers consist of hydrophones that are sensitive to the noises created by ships as they move through the water (NWP 3-15, 1996)(Molina, Sánchez, & Rodrigo, 2007). These noises generally are that of hull noises caused by the ship moving through the water, machinery noises caused by engines and other systems, and noise caused by a ship's propeller.

The acoustic influence trigger is susceptible to mine sweeping using equipment that simulates the noises caused by ships. This equipment is pulled through the water emitting noise similar to that of a large ship, thus causing the mine to detonate a safe distance away from the MCM personnel (NWP 3-15, 1996).

Information gathered about the MINEA family of mines indicated that some mines have the capability to detect sonar signals and receive coded acoustic signals used to activate and deactivate the mine (Molina, Sánchez, & Rodrigo, 2007). The purpose of sending coded signals is to allow the mine to be deactivated for ships which would be "friendly" to the mine, and reactivating once it had passed. This also allowed the minefields to be deactivated at the end of hostilities (Molina, Sánchez, & Rodrigo, 2007). Advanced versions of these types of mines dampen their influence and characteristics to remain undetected when being swept by MCM.

Electromagnetic

Multiple sources indicated that apart from the acoustic trigger the next most common was the "magnetic influence" trigger. This type of triggering mechanism detects changes in the magnetic fields around the mine. When a ship with a steel hull moves though the earth's magnetic field, a slight distortion occurs in the surrounding area. Although slight, this distortion is significant enough to trigger a mine (NWP 3-15, 1996; Molina, Sánchez, & Rodrigo, 2007).

A similar technology, electrical potential influence, detects the electric currents caused by dissimilar metals immersed in sea water. Since the hull of a ship and the propeller are made of different types of metal, an electrical current is created when the ship moves through sea water (NWP 3-15, 1996; Molina, Sánchez, & Rodrigo, 2007).

The magnetic influence trigger is susceptible to mine sweeping using equipment that simulates the magnetic distortion created by a ship. This equipment is pulled through the water creating a magnetic field that is similar to that of a larger craft causing the mine to detonate a safe distance away from the mine counter measure personnel (NWP 3-15, 1996).

A few examples of mines using electromagnetic influence technology are the MINEA family of mines, the MANTA mine, and the Chinese EM-53 (Erickson, Goldstein, & Murray, 2009; Molina, Sánchez, & Rodrigo, 2007; Final Report to Congress: Conduct of the Persian Gulf War, 1992).

Pressure

Pressure actuation consists of sensors that can detect the pressure waves caused by a ship moving through the water. These sensors are sensitive and can be triggered by wave action if used alone (NWP 3-15, 1996; Molina, Sánchez, & Rodrigo, 2007). However, a pressure triggering method is typically not used as the sole triggering method.

When used in combination with other sensors such as acoustic and magnetic, pressure detection can be used to counteract mine sweeping activities. It has been stated that this combination of sensors can make it “virtually impossible to sweep a mine” (Erickson, Goldstein, & Murray, 2009). This is because there is currently no equipment capable of simulating the pressure waves necessary without moving a vessel through the area (NWP 3-15, 1996). When these sensors are used in combination, sweeping would require simulating the noise, magnetic and pressure signatures at the same time in order to trigger the mine.

Some examples of mines using pressure sensors are the MINEA family of mines, and the Chinese C-6 (Erickson, Goldstein, & Murray, 2009; Molina, Sánchez, & Rodrigo, 2007).

Seismic.

Seismic influence triggering consists of accelerometers in the mine detecting movement in the mine case, or the sea floor where the mine is laid. As sound waves interact with the sea floor and the mine casing, vibrations occur which can be detected by the accelerometers. Since the vibrations are caused by sound waves, seismic triggering is similar to acoustic triggering (Molina, Sánchez, & Rodrigo, 2007; NWP 3-15, 1996). It can be assumed this method of triggering would be susceptible to the same mine sweeping techniques used for acoustic triggering.

Two examples of mines using seismic influence triggers are the bottom mine version of the MINEA family of mines, and the MANTA mine (Erickson, Goldstein, & Murray, 2009; Molina, Sánchez, & Rodrigo, 2007). It can also be assumed that drifting mines could not be effectively triggered using this method. Since the seismic vibrations are being transmitted through the sea floor, the triggering sensor package would need to be in contact with the sea floor.

c. *Command and Control Actuation*

The "Command and Control" method of triggering uses a command sent to the mine from a control station causing detonation. This method is mostly used for port and harbor defense since it allows the mines to be detonated only when an observer selects the target (NWP 3-15, 1996). This type of trigger cannot be effectively swept since an external signal must be sent to the mine before detonation.

The MANTA-103 has an option of having a remote control cable in order to receive signals (Sei Spa, 2011). It would also be possible to use acoustic links similar to the one used in the MINEA family of mines (Molina, Sánchez, & Rodrigo, 2007).

4. Mine Deployment

Mines can be delivered to their final plant position via aircraft, submarine, or surface vessel. Each method has its situational advantages and disadvantages. When speed is critical or the area to be mined is not freely available to the minelayer, using aircraft is best. If stealth is required, then submarines are much more suited for the task. In the case of a large number of mines needing to be placed, or the availability of other delivery craft is limited, various surface vessels may be used. It is important to be aware of the deployment methods and the reasons for their use. By knowing the method of deployment it becomes easier to determine which mines pose a risk in a given area.

a. *Aircraft Delivery*

Aircraft are the preferred method of delivery when placing offensive naval mines. They can access areas to which submarines and surface ships cannot, including existing minefields and shallow waters. Dropping mines is similar to dropping bombs, and typically the same aircraft that are used to carry bombs are used to carry and deploy mines of the same weight class. A drawback to this is that unless a cargo-carrying aircraft is used, the weapon loads are small in comparison to the large weapon loads that submarines and surface ships have when laying mines. The mines which are deployed by this method are specially designed for air-delivery so they do not crush or damage upon contact with the water. One major advantage is when notified of a mine laying mission, aircraft have fast response times. However, a major disadvantage of aircraft delivery is it is much less accurate when compared to other methods (NWP 3-15, 1996).

b. *Submarine Delivery*

Submarine-delivered mines are the preferred method of delivery in covert offensive operations. They are effective at penetrating areas with high surveillance of surface and aerial

crafts. The mines whichs are deployed by this method are specially configured to be launched from torpedo tubes or mine belts of the submarine. Such mines include the propelled bottom mine which, once fired, will guide itself to its specified plant position (NWP 3-15, 1996).

This method can be disadvantageous due to its long response time and limited availability of submarines. When a submarine is called for a mine laying mission, it must first return to port where the torpedoes are unloaded and the mines are loaded. Furthermore, there is a limitation capacity of mines that can be carried at once (NWP 3-15, 1996).

c. Surface Vessel Delivery

Surface-delivery of mines is the preferred method for defensive minefields only. It is advantageous due to its large load capacity and the accuracy with which the mines are placed. During mining operations, the ship is vulnerable to attacks by the enemy and, therefore, it requires that the surrounding area be under friendly control. When a surface ship is called for a mine-laying mission, the ship must first travel to a location where the mines can be loaded before it can travel to the location of the minefield (NWP 3-15, 1996).

Given the focus of the 10-40ft depth range, surface-delivery is the most common method of deployment. Mines possessed by enemy countries are manufactured to be easily laid from a variety of watercraft, including rubber dinghies, tugboats, barges, and dedicated mine laying craft (Final Report to Congress: Conduct of the Persian Gulf War, 1992; NWP 3-15, 1996). If a surface craft has a large load capacity, it would be reasonable to deploy lines of mines. However, if a craft has a small load capacity, then the pattern of the minefield is more random.

5. Platforms at Risk

The assets that are at risk include US Navy and Marine amphibious assault vehicles (AAV) which operate in the 10-40 ft littoral zone. Large US Navy and Marine platforms are not considered for this range because the draft of these platforms typically exceeds 40 feet. Examples of the high risk assets include, but are not limited to: LCS class ships, the Landing Craft Air cushion, the future Ship to Shore Connector, the Amphibious Assault Vehicle (AAV-7A1), and possibly the future Expeditionary Fighting Vehicle (EFV). In this region, all mines pose a threat to each asset.

6. **Countries of Concern**

In order to fully understand the mine threat, it is important to understand the capabilities the enemy possesses. As of 2001, over 50 countries utilize mines in the littoral region to aid in the prevention of amphibious invasion and about 77% of the ship casualties between 1950 and 2001 were caused by mines (Cornish, 2003). Figure 6 shows the US ships that were damaged, the countries responsible for the damage, and the weapons used. Due to their current tensions with the United States, the following three countries are the prime focus: China, Iran, and North Korea.

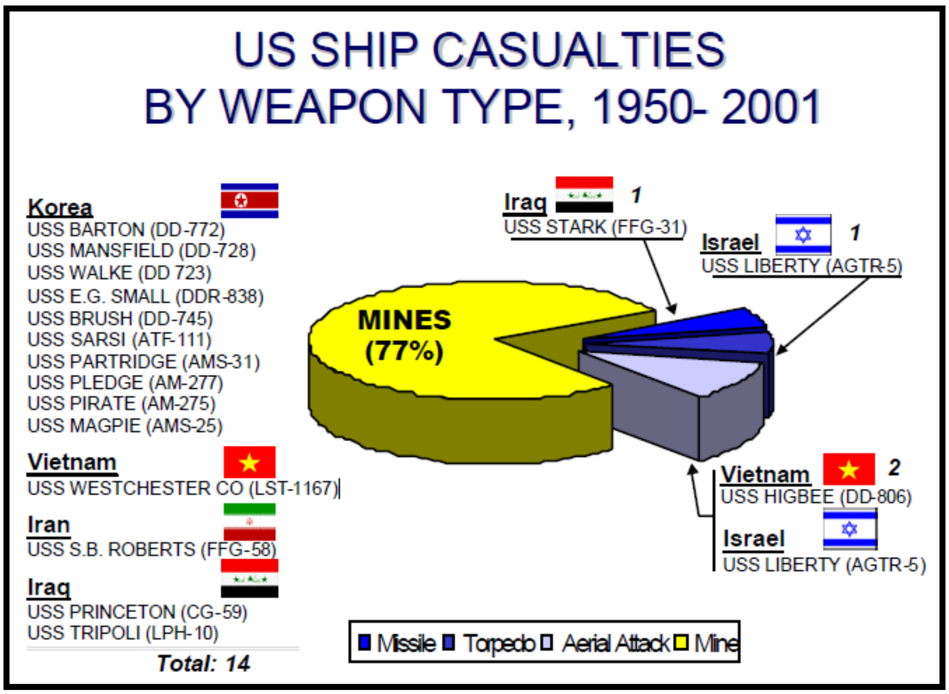

Figure 6. US Ship Casualties by Weapon (1950-2001)

As of 2001, over 50 countries utilize mines in the littoral region to aid in the prevention of amphibious invasion and about 77% of the ship casualties between 1950 and 2001 were caused by mines (Cornish, 2003). This chart depicts which US ships were damaged by what mines with the country responsible for the associated damage.

a. China

China's lethal arsenal consists of a wide variety of naval mines. Their inventory is one of the largest in the world and is estimated to contain between 50,000 to 100,000 individual weapons. It is important to understand that mine stocks can be hidden very easily and so it is difficult to pinpoint the exact quantity. China's inventory contains 30 varieties of contact, acoustic, magnetic, water pressure and mixed reaction aquatic mines, rising moored mines, remote control mines, and mobile mines; all ranging from the less advanced technologies of the

early twentieth century to the more sophisticated bottom and propelled mines of today (Erickson, Murray, & Goldstein, 2007).

b. Iran

Proceeded by the United States, Russia, and China, Iran is thought to have the fourth largest inventory of naval mines in the world, with an estimated 5,000 mines in its possession. The EM11 bottom mine, the EM31 moored mine, and the EM52 propelled rising mine make up nearly 1,000 of these mines (5th Fleet Focus: Iranian Underwater Warfare Capabilities, 2007). The EM52 is thought to be the most dangerous in their inventory since it is rocket-propelled and does not allow time for a ship to deploy countermeasures (Erickson, Goldstein, & Murray, 2009). Iran purchased 3 Kilo-class submarines from Russia in 2000 and in the process took possession of 1800 mines. While it is unlikely that the Kilo-submarines are in good condition, they are still capable of deploying approximately 36 mines per sortie. If paired with a merchant ship supplied with mines, they could perform 2-3 mine laying sorties per week. Factor in Iran's capability to produce non-magnetic, drifting, and remote-controlled mines and they stand to gain considerable clout in naval warfare (5th Fleet Focus: Iranian Underwater Warfare Capabilities, 2007).

c. North Korea

About 60% of North Korea's naval force is arranged along the shore line. This includes approximately 430 combat vessels (i.e. patrol boats, missile boats, and torpedo boats), 35 submarines, and over 330 support vessels (i.e. landing ships, fire support vessels). The majority of the submarines are Romeo-class, and although some researchers consider them outmoded and slow, they are still very capable of deploying mines (Howard, 1999). Furthermore, North Korea's mine inventory consists largely of older technology mines. Despite this, they possess the historical experience of their effectiveness and the confidence to use them. Once the defensive minefields have been set, they are monitored by radar and observations teams positioned on the coast. Should the enemy be detected, North Korea will respond with support from artillery and missile batteries. This constant surveillance makes close approach and MCM operations very dangerous (Korean People's Army Navy, 2011).

7. Lessons from History

To date, Iraq has been the location of the last two US engagements in which mine hunting was critical for an amphibious force. The first engagement was the Persian Gulf War in 1991 and the second was Iraqi Freedom in 2003. The Persian Gulf War was considered a mine warfare failure to the US, but served as a learning experience that resulted in the mine warfare

success of Iraqi Freedom. By looking at the differences between the two engagements some insight can be gained.

a. Persian Gulf War (1991)

Out of the reported 1167 mines deployed in the waters around Iraq and Kuwait during the Persian Gulf War, many were Iraqi-built equivalents to Russian-made contact mines from a WWI design. Additionally, their arsenal contained more modern mines, including acoustic and magnetic influence mines purchased from Russia and Italy. During the lead up to the Persian Gulf War, US forces did not take any action to prevent the use of mines for fear it would provoke the Iraqi Armed Forces. Unfortunately, this allowed the Iraqi Navy to use rotary-winged aircraft, modified tug boats, and barges to deploy mines in the areas surrounding Kuwait and Iraq (Final Report to Congress: Conduct of the Persian Gulf War, 1992).

The Iraqi Navy deployed the aquatic mines in haste, causing them to improperly plan and execute the mine laying activities. As a result, up to 95% of the acoustic mines were later determined to be inoperative, and 13% of the moored mines broke free. Despite this, the US received damage to 2 warships and cancelled an amphibious assault on Ash Shuaybah in Northern Kuwait. To further impede the effectiveness of the US MCM forces, the minefields were deployed in areas within reach of shore-based missile and artillery batteries and created opportunities for small boat attacks (Final Report to Congress: Conduct of the Persian Gulf War, 1992).

b. Iraqi Freedom (2003)

During Iraqi Freedom, the US and coalition forces expected the Iraqi Navy to once again mine the areas around Iraq. Consequently, MCM activities began early with air superiority activities used to prevent the enemy from deploying mines via aircraft. This limited Iraq to using small rubber boats, modified tugs, and barges. To further reduce their effectiveness, SEAL teams were sent to engage those forces, and those mine-laying assets were captured. These preventative measures were successful in reducing the amount of naval mines Iraqi forces deployed and therefore reduced the amount of United States mine counter-measure assets required in many areas. However, this does not show that the ability to detect and clear mines improved, and indicates that prevention allowed this conflict to be considered a mine warfare success (PEO LMW, 2009).

8. Future Mine Capabilities (5-10 years)

Lethality and stealth are ever-evolving aspects of combat technology. As such, combat mines are always changing with respect to both offensive and defensive capabilities. When there is an improvement in the ability to detect mines it forces an improvement in the technology used to avoid detection. One technology that will be used in the future is Unmanned Underwater Vehicles. These unmanned vehicles are ideal for mine placement without the need to put personnel in harm's way (Mason, 2009).

Wireless communication is currently being incorporated into newer mines giving these mines more C2 functionality. The wireless link coupled with direction finding sensors allows for the networking of mines and remote C2 to obtain and relay location, speed, and bearing information of targets. Once this information is determined, a mine can be remotely detonated at the best moment to achieve maximum damage. This detonation could be limited to one mine, or cover a group of mines, depending on the target and desired effect. In addition, this technology allows for the possibility of Identifying Friend or Foe (Mason, 2009). By using acoustic links, mines like the SAES' MINEA family of mines can be deactivated when "friendly" ships pass through the minefield and then restored to an active state once the ships have cleared (Molina, Sánchez, & Rodrigo, 2007).

Computing technology is also becoming more prevalent in the construction of mines. As microprocessors become less expensive, this allows more intelligence to be built into the mines and networks of mines. Given that mines can be equipped with various sensors, it is possible for the detection of minesweeping efforts to be circumvented by detecting multiple trigger types. For example, if a mine detects the magnetic or acoustic signature of a large ship without detecting the pressure signature, the mine would assume this is a mine sweep and stay dormant. As mines are equipped with more processing power, they can potentially gain the ability to detect more specific targets. This may allow smaller craft to pass by in order to damage larger ones, or they may allow multiple craft to pass by before detonation.

Another technology that is being implemented pertains to the physical shape and materials used in the construction of mines. In order to disguise the mine from detection by sonar, mines are being created in irregular shapes. These shapes could simulate plant life or other objects that would normally be found on the ocean floor, including junk that could have been dumped into the sea (Mason, 2009; Rabiroff, 2011). The use of non-magnetic materials is being incorporated in order to reduce the chance of detection by magnetic resonance mine hunting. The use of echo eliminating, or "anechoic, "materials are also being explored in order to dampen the reflection of sound which would indicate the presence of a mine (Mason, 2009;

Molina, Sánchez, & Rodrigo, 2007). New technologies are being used to actively or passively bury mines. Some case shapes encourage the natural flow of sand and water to bury the mines, and some of the aircraft-deployed mines are created to enter the water in such a way that they will automatically bury themselves. It can also be possible to have a torpedo-deployed mine incorporate similar technology to use its propulsion to bury the mine (Mason, 2009).

9. Threat Analysis Conclusion

Sea mines are becoming more challenging to identify, classify, localize, and detect in the VSW zone. Further work is needed for future systems to maintain the ability to counter and respond to emerging threats to continuously allow the US Navy to perform amphibious operations in the VSW zone without high risk of damage from sea mines.

B. CURRENT CAPABILITY ANALYSIS

An assessment of current US MCM and future US and North Atlantic Treaty Organization (NATO) systems utilizing current Marine Corps amphibious doctrine, approved development programs descriptions, stakeholder feedback, symposium presentations, and publicly available unclassified information comprised the current capability analysis. The assessment analyzed whether current and future systems are sufficiently capable to detect, localize, identify, classify, and neutralize threats expected in the VSW zone to fulfill stakeholder needs in a standalone or system-of-system configuration. Appendix A presents a description of the current and future systems researched that contributed to the findings of the analysis.

1. Current Capability Gaps

MCM systems are moving towards remotely operated sensors and systems as opposed to divers and mammals in mine clearing operations. However, there are still several challenges that must be met, and capability gaps that exist. The result of the capability analysis identified capability gaps that cannot be met with existing or planned platforms, and systems need to be updated to meet current policy, procedures, or tactics.

Table 2 identifies the capabilities and limitations of current MCM systems in the minefield derived from the research of current systems contained in Appendix A.

Table 2. Capabilities of Current MCM Systems in the VSW Minefield

There is currently a variety of MCM systems that are in use by the US and NATO. This table presents a high level view of the advantages and disadvantages of the diver, MMS, UUV/AUV, and Surface/Aviation based systems in the VSW Minefield.

	MCM System Types			
	Diver based	**MMS based**	**UUV/AUV based**	**Surface/Aviation Platform Based**
Overall System Advantages	- Has the capability to provide quick visual identification - Can be executed covertly once in the AO - Proven effectiveness	- Conducts MCM clearance operations at faster speeds and longer endurance over diver systems - Removes the diver from the minefield and conducting clearance/neutralization operations	-Conducts the fastest identification, classification, localization, and detection in MCM clearance operations - Greater endurance, speed, and coverage than diver and MMS	-Can cover a large amount of area quickly
Overall System Limitations	- Diver systems involve humans directly exposed to minefield (safety/risk issues) - Divers have limited area coverage capability due to environmental conditions, human speed, and human and diver support equipment endurance	- Mammals in the minefield (ethical issues) -MMS have limited classification capability and long detection time of threats compared to divers - Limited coverage area and speed; MMS is faster and covers more area than divers, but MCM clearance operations requirements are not being met.	- UUV data analysis is not in real-time. The system is required to be recovered and analyzed during post mission analysis, resulting in extended mission times. - Limited ability to conduct covert operations in towing mode of operations - Sea conditions and environment effect the system performance - Requires crane/support platform to launch vehicle	-Involve large numbers of humans operating in minefield -Are easily detected when working in the VSW zone -Limited maneuvering ability in VSW zone due to water depth and environmental and man-made obstacles

Table 3 provides a snapshot of what current MCM systems are used against each type of mine threat. As indicated by the table, EOD or diver systems are currently the best method for covering the breadth of mine threats as part of Explosive Ordnance Disposal Mobile Units (EODMUs). EODMU ONE is currently the only Naval command possessing a VSW MCM capability. At present, EODMU ONE utilizes a combination of Marine Mammal Systems (MMS), the MK 18 Mod 1 Unmanned Underwater Vehicle (UUV) and specialized divers for conducting VSW MCM.

The unmanned systems like the ASQ-14A and SQQ-32 provide mine countermeasures capability short of engagement for most of the mine threats in the VSW zone. The MK104/105 and SLQ-37 unmanned systems have the best threat coverage, but only provide area engagement capability. It is apparent from Table 3 that a future MCM system is needed to provide the necessary coverage across the threat set.

Table 3. Current MCM System Capabilities

The current MCM systems in use today provide a range of capabilities across the different mine types. For the top portion of the table, an 'X' denotes a system's capability in the corresponding row. For the bottom portion of the table, an 'X' denotes the mine types each system is effective against. As shown, only an EOD diver system can carry out the complete detect-to-engage sequence capability (Landay III, 2005).

	EOD (Diver)	ASQ-14A	SQQ-32	MNS (SLQ-48)	SLQ-38	MK 104/105	SLQ-37	MK103
RECON	X	X	X					
SENSE	X	X	X					
POINT ENGAGE	X			X				
AREA ENGAGE					X	X	X	X
FLOATING	X				X			X
NEAR SURFACE	X				X	X	X	X
MOORED	X	X	X	X		X	X	
CLOSE TETHERED	X	X	X	X		X	X	
C-C TETHERED	X	X	X	X		X	X	
BOTTOM	X	X	X	X		X	X	
BURIED	X					X	X	
ANTI-INVASION								

Table 4 displays MCM systems that are currently under development such as the JABS, OASIS, and AMNS and systems currently being fielded like the MK104/105, SLQ-37, and MNS. As seen in Table 4, the developing systems will provide increased capability for engagement of bottom mines, but not for buried mines, the focus of this capstone project. Still the EOD solution is the best thus far for capability across the threat set.

Table 4. Future MCM System Capabilities

The future and developmental MCM systems shown in this figure take the man out of the minefield. For the top portion of the table, an 'X' denotes a system's capability in the corresponding row. For the bottom portion of the table, an 'X' denotes the mine types each system is effective against. As seen, these newer systems lack the all-in-one capability for the detect-to-engage sequence. This forces the use of multiple systems to carry out a clearance operation (Landay III, 2005).

	EOD	RMS (WLD-1)	UUVs	COBRA	ASQ 14A	ALMDS (AES-1)	SQQ-32	AQS-20A	JABS	EOD UUV	MNS (SLQ-48)	AMNS	OASIS	SLQ-38	MK 104/105	SLQ-37	MK 103
RECON	X	X	X	X	X	X	X	X		X							
SENSE	X	X		X	X	X	X	X		X							
POINT ENGAGE	X										X	X					
AREA ENGAGE													X	X	X	X	X
FLOATING	X					X								X			X
NEAR SURFACE	X	X	X			X		X		X		X	X	X	X	X	X
MOORED	X	X	X		X		X	X		X	X	X	X	X	X	X	X
CLOSE TETHERED	X	X	X		X		X	X		X	X	X	X		X	X	
C-C TETHERED	X	X	X		X		X	X		X	X	X	X		X	X	
BOTTOM	X	X	X		X		X	X		X	X	X	X		X	X	
BURIED	X			X					X				X		X	X	
ANTI-INVASION				X					X								

Due to the complexity of the VSW environment, creating a system that meets all the requirements and challenges is difficult. Based on the project problem statement, this analysis has identified five capability areas that should be considered in current and future system developments.

a. System Ease of Deployment

The first important aspect to note of current and future MCM systems is that they require helicopter deployment, helicopter tow cable, Littoral Combat Ship (LCS) ship with crane

deployment, or an LCS tow cable. Although the ability to deploy a system by helicopter or ship is not by itself an exclusive limiting factor, a system that could be transported and deployed using a variety of platforms would allow for better use of Navy/DOD resources, resulting in time and cost savings.

b. Mine Hunting Process

Currently, there is not a single system or process that fulfills the need for detection, localization, identification, classification, and neutralization without the use of divers or mammals in the minefield. A multi-functional system or integration of multiple systems could be deployed to perform the mine hunting process. The result of a multi-functional system that performs all the functions in the detect-to-engage sequence could result in a reduced logistical footprint. The need for redundant functions, such as the re-acquisition of the mine by a second neutralization platform, could be eliminated if such a system existed.

c. Types of Mines

Reviewing Table 3 and Table 4 it is clear that there is not a singular system that can cover the gamut of mines that could potentially be encountered in the VSW zone and not be limited to a specific mine threat. If possible, Future MCM systems should be designed to complete the mine hunting process for all types of mines in the VSW zone. This system concept would include mine threats from buried and bottom mines, tethered type mines, surface mines, and floating mines.

d. Oceanic Limitations

The VSW region is a complex region where the surface and bottom Ekman boundary layers merge, stratification can be transient, buoyancy fluxes are significant, and fluid motions can be dominated by various waves, tides, or low frequency currents (National Academy Press, 2000). The Ekman boundary is the layer in a fluid where there is a force balance between pressure gradient force, rotational force and turbulent drag. This boundary region has several natural and man-made factors that can degrade the ability of MCM sensors to acquire, sense, and discriminate mines from natural phenomenon. Increased image aberrations and degraded image resolution impact object detection and identification constraining how fast and reliable a search can be conducted.

The influence of meteorological variability on near-shore mine warfare can be either direct or secondary. Direct influences are primarily related to the effects of atmospheric conditions on MCM sensor capabilities. An example of such is cloud cover creating confusing shadows for optical sensing, or clouds and rain that degrade both optical and acoustic-sensing performance.

Secondary influences are mostly related to atmospheric conditions that drive fluid motion affecting mine burial conditions and the performance of mine countermeasures. Local winds often influence the burial of the mine and the turbidity of the environment, complicating diving operations. On a large scale, winds can dramatically change local optical and acoustic properties of a water column due to circulation caused by the influence of local coastal topography. The local atmospheric conditions can also cause muddy outflows of water from nearby rivers and estuaries into the VSW region.

Spatial and temporal variations in water depth and seafloor profile can influence the location and height of breaking waves, the position and strength of surface currents, and the propagation of the tide into the VSW region (National Academy Press, 2000). The measurement of water depth in the VSW region changes rapidly due to a wide spectrum of objects on the ocean floor. The fluid dynamics and the sea floor makeup in this region can quickly cover or uncovered bottom mines due to the shifting of the sea floor.

Tidal currents have a direct influence on mine warfare operations in the VSW and surf zone region. Tidal currents can cause a dip that keeps moored mines below the surface, and can increase the scour of bottom mines (National Academy Press, 2000). These tidal currents in the VSW region often exceed 1 knot and thus can affect diver and marine mammal operations. Currents in the VSW and surf zones are also more directly influenced by wind, wave-driving forces, and buoyancy fluxes due to runoff or river outflow. Tidal models in the VSW and surf zone that predict currents are inaccurate due to nonlinearities, bottom friction, and boundary effects, such as reflection and local forcing (storm surge) (National Academy Press, 2000). There is very little support in modeling to help predict these effects on MCM systems.

e. Technologic Limitations

Current MCM systems are not able to expeditiously and accurately complete the mine hunting process. Mine detection system development is making vast leaps towards faster area clearance through improvements in the areas of lasers, optics, sonar, and acoustic technologies, which have made it possible for humans to review sensor data to effectively identify and classify target threats. The possible integration of these technologies, along with updated software capabilities would allow for improved automated processing and target identification and classification.

The effects of optical properties are very important and hard to predict in the VSW region. The variance in optical properties affects the visibility for divers, Light Detection and Ranging Systems (LIDAR) and other MCM systems depending on optical sensors (National Academy Press, 2000). The euphotic zone which is defined as the area between the sea surface

and the depth where light diminishes to 1 % of its surface value (Chamberlin, 2011). The depth of the euphotic zone depends largely on the concentration of organic and inorganic materials dissolved or suspended in the water column. These suspended materials can create thin layers with radically different optical properties that can degrade or obscure the abilities of divers and other MCM sensors to detect the bottom and mine like objects.

Another problem for MCM systems in the VSW region is with acoustic sensors. Sonar systems on MCM vehicles are expected to operate in shallow, very shallow, and deep water zones which require them to perform through the entire water column, including near surface, seafloor, and sub-seafloor. This means they are not optimally designed for one specific area but must be sufficiently broad to operate over the entire region. This could add to the difficulty in operating in the VSW region, since the VSW area is characterized by the presence of reverberative backgrounds, low signal-to-noise environments, and high cluttered acoustic backgrounds. The VSW region has a naturally situated condition in which sound velocity profiles are often incorrectly characterized because they are continuously changing. This sets up situations for autonomous platforms to incorrectly interpret mines and mine-like objects, or incorrectly identify their locations (National Academy Press, 2000). Therefore, identification and classification are difficult by themselves for an MCM system, with the neutralization process adding another layer of difficulty in completing the mission.

Finally, it should be expected that in the VSW areas that are compatible with marine amphibious landings, there will be a certain amount of man-made metal object clutter. This metal clutter can be the result of dumping, ship wrecks, fishing losses, and material washed out into the area due to storms. These objects can also produce false positives for MCM operations.

2. Current MCM Manned System Scenario

To aid in requirements development and to identify modeling parameters an MCM mission scenario was developed. The mission scenario was created based on clearing a VSW region with the current human system. The overall purpose of this scenario was to provide a means of determining additional information on current MCM systems deficiencies. This information was then used to help shape the requirements and modeling parameters of the new MCM system.

a. Vignette Facts and Assumptions

The following facts and assumptions are used in this vignette:

1. A typical boat lane or Q-lane required for an Amphibious Operation is 2000 to 2700 yards by 500 yards (MCWP3-13, 2011). A boat lane is the area in which Marine Amphibious forces travel from amphibious ships to the landing beach via Amphibious Assault Vehicles, Landing Craft Air Cushion (LCAC), and Landing Craft Mechanized and Utility (LCM/LCU) boats.
2. A typical Amphibious Operation will consist of 2 Marine Expeditionary Brigades (MEB) with approximately 29,000 Marines and Sailors (Trickey, February 2010). For planning purposes the amphibious force typically needs 12 Boat Lanes to be cleared (Moon, 2011).
3. The VSW region will be typically a 500 yard by 500 yard region of the boat lane.
4. The typical MCM diver can swim at a speed of 1 knot. This equates to 500 yards in 15 minutes (Marine Corps System Command Infantry Weapon Systems, 2011).
5. A dive team consists of 2 people (Marine Corps System Command Infantry Weapon Systems, 2011). Within the mission, several dive teams will be assigned to complete the tasking. The number of dive teams required to conduct the mission will depend on the size of the operational area. Dive supervisors will take into account the limitations of the divers and their equipment during the planning phase.
    a. Assumption: Dive teams are not affected by tidal or natural currents.
    b. Assumption: Dive teams are not affected by optical properties of the water.
6. Diving equipment weight and MCM equipment for one person is approximately 226 lbs (Marine Corps System Command Infantry Weapon Systems, 2011).
7. A two person team can roughly scan 23 yards in a sweep (Marine Corps System Command Infantry Weapon Systems, 2011).
8. The sweep priority for the amphibious force is to detect, mark, and avoid (Clements, 2011).
    a. Assumption: It will take a dive team 5 min to identify and mark a mine while conducting a search.
    b. Assumption: The MCM dive team, consisting of two dive teams, is covertly delivered to the search site by a rubber boat that contains one driver.

Figure 7 displays a typical clearance swim pattern conducted by MCM divers; MCM divers clear (identify, inspect and mark) the area in a similar pattern by swimming back and forth parallel to the shore. It is estimated that it will take 21 passes to clear the VSW region as described by vignette facts and assumptions.

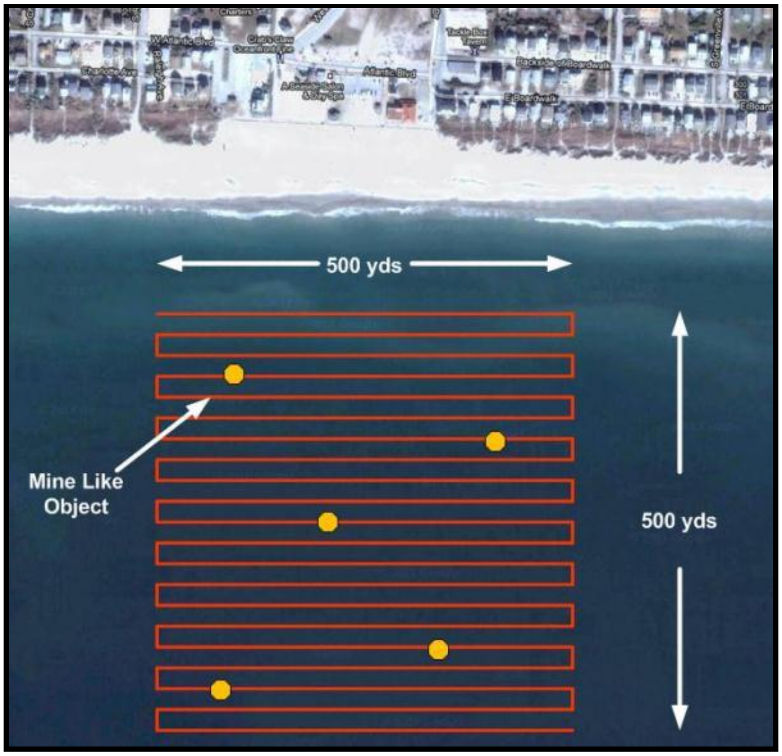

Figure 7. Beach Landing Site VSW Clearance

Typical clearance swim pattern used by a diver system. The typical coverage area will typically be 500 yards x 500 yards in the VSW area (Google Maps, 2011).

For this scenario it is assumed that the mine density is 5 mines per 500 square yards. Based on the assumptions it would take one dive team 5 hours and 30 minutes to swim the pattern as shown in Figure 7. However, this is assuming that the dive team can continuously swim at 1 knot, which is unrealistic. To compensate, a fatigue factor of 3% was added to time calculations after the divers had swam 5 laps. Adding the estimated time it takes to identify, inspect, and mark a suspected mine along with fatigue, the estimated time to clear the area is 6 hours and 51 minutes. Due to limits of available air in oxygen tanks, it is essentially impossible for one team to sweep this area in that time. Therefore, it is assumed that the minimum number of teams needed to clear this VSW region is two teams. Assuming that each team covers half of the area to be cleared, it will take approximately 3 hours 40 minutes to clear the region.

Based on this analysis, it will take a minimum of 5 diver teams to clear the VSW region for one boat lane. Extrapolating this information, the estimated personnel required to clear 12 boat lanes is 60. Since each person carries 213 pounds of equipment, the amphibious forces must have the room to carry 10,244 pounds of dive MCM equipment to support the teams.

b. Diver-based MCM System Limitations and Takeaways

1. To identify and mark mine-like objects the VSW region in approximately 4 hours requires 60 people. If mines need to be classified and neutralized, additional planning must be performed to allow crews to identify the mine-like objects. This will require additional time.
2. Current MCM platforms do not have the space to support current MCM operations. To meet the above time requirement, 60 divers are required. This value does not include the personnel needed to support the divers. The current LCS ships only provide berthing for 35 additional personnel. Therefore, 2 LCS ships will be required to complete the mission. This analysis also does not include the personnel required to clear the rest of the boat lanes. If the same personnel were used to clear the total lanes, it will require additional time to transport, collect data, and rest the crew.
3. The LCS ships must have the necessary storage capacity to store the equipment.
4. The dive team requires additional planning time that must be accounted for to allow the crew to operate when the environment is affected by tidal currents and natural obstructions.
5. The dive team must operate during times of limited visibility to enable them to remain undetected. The back-of-the-envelope (BOE) analysis took this factor under consideration for the analysis and determined that portions of the clearance operation will need to be performed during times of light. This will make the team vulnerable to the enemy and very difficult for the team to remain covert.
6. The dive team requires a transportation boat to enter the operation area and remain close to the field to support divers. This creates an extreme limitation providing support from the host platform to the diver transportation boat during clearance if the host platform intends to remain over the horizon (OTH).

3. Current Capability Analysis Conclusion

It was determined through analysis and research in this MCM capabilities analysis report that the current and future MCM systems are unable to adequately meet the 72 hours of clearance time for amphibious VSW operation. A redesigned system architecture and reassessment of its concept of employment is recommended along with an evaluation of the development of future systems to ensure they meet amphibious operational timeline requirements. Current and future

MCM systems are transitioning to remotely operated sensors with intentions to remove divers from amphibious mine field operations as much as possible, but there are still several common challenges that need to be addressed with remotely operated sensor systems before they can be meet MCM operational requirements.

In general, limitations of the new MCM systems, particularity with UUV/AUVs, are that they require more time for data analysis, with limited covert operation especially with devices towed from above the water. Due to the size of UUV/AUVs, they require large platforms such as an LCS or helicopter to launch them in desired mission operations. Oceanic factors causing issues with sensor information in the VSW zone create another hurdle to overcome in conducting MCM operations in this region.

C. OPERATIONAL CONSIDERATIONS

In developing an understanding of current MCM threats and capabilities, it became necessary to look further into the implementation of MCM using historical examples to guide the development of an architectural solution and operational concept.

1. Background

US forces have been developing MCM capabilities since World War I, where the US Navy assisted the United Kingdom with clearing the North Sea Mine Barrage (Gilbert, 2001). In 1988, MCM concepts were launched to counter mines deployed in the Persian Gulf by Iran. The mining situation in the Persian Gulf was dubbed the "Tanker Wars" because both Iraq and Iran focused their mines to attack shipping platforms in this area. The threat of mined harbors and sea lanes were used with the intent of terrorizing friendly forces into diverting from normal operations. The goals of these actions were to draw other countries into a war, or to cause Allied forces to expend capital in providing defenses for maritime shipping. Iran covertly attacked shipping bound for neutral countries at the time including Saudi Arabia, Kuwait and the United Arab Emirates, in the hopes that these attacks would force the Sheikdoms to take sides and thus force Iraq into withdrawing from Iranian territory (Andrew, 2007). While Iraqi forces attacked shipping with air assets in a declared war zone, Iran was successful in attacking shipping covertly with mines.

Iran's intent in 1988 is slightly different from the defensive objective of an enemy that develops a coastal defense against an amphibious assault. The mining used by the Iranians was to covertly harass merchant shipping and disrupt transit through the gulf. By subtly placing mines in an area away from territorial waters and leaving them unattended, the enemy avoids culpability by lack of presence when a mine detonates. Mines used for littoral defense are similar to US mining policies since they are used to delay or disrupt amphibious forces with the

intent of shifting counter attacking forces to stop the landing. Against an amphibious force, the mines are used to canalize an attacking amphibious force into a kill zone targeted for destruction. Therefore, the threat emplaces a coastal defense with an over-watching force that will engage and attempt to destroy all MCM operations with direct or indirect fire. This is uniquely different from the Persian Gulf experience in which mines were placed by a country trying to hide its identity.

The takeaway is that the enemy threat will not only be defensive, but also offensive in tactics. For this report, the MCM units cannot assume freedom of movement when sweeping a coastal defense that has employed sea mines. To develop systems to support an amphibious operation, it is important to assess and analyze how MCM operations deploy and employ tactics to develop support systems to execute an amphibious operation.

a. MCM Operational Phases

MCM doctrine states that there are five maritime MCM mission objectives when planning operations. These objectives are Exploratory, Reconnaissance, Breakthrough, Attrition, and Clearing (JP 3-15, 2011). The order of conduct for MCM operation phases are:

1. Exploratory Phase – In this phase, an advance task force (ATF) conducts quick reconnaissance to determine if mines are present in the path of the amphibious force.
2. Reconnaissance Phase – In this phase, the ATF conducts a more thorough reconnaissance to determine:
    a. Gaps in mine fields and any other obstacles present. The amphibious force desires to find a path through the mines before attempting to neutralize mines to create a path. In this phase, the navy planners try to find boat lanes to the shore in which the amphibious force can bypass and avoid obstacles.
    b. Mine density along the desired paths to the objective landing point
    c. Type of mines along the paths and their locations
    d. Limits of the width and length of the mine fields and obstacles
    e. Hydrographic reconnaissance in the area of operation, that determines depths, beach gradients, and the nature of the bottom and man-made obstacles
3. Breakthrough – The objective of this phase is directed at rapidly opening channels and staging areas for an amphibious operation. The goal is to reduce the threat to friendly shipping vessels passing through a mine threat area in a specified time available for MCM.
4. Attrition – The objective of this phase is to continuously keep the threat of mines to shipping traffic as low as possible when vessels must continue to transit the mined waters for a comparatively long period of time.

5. Clearing – In this phase, the mines are removed from the assigned area, reducing risk to specified acceptable level.

b. Mine Field & Obstacle Detection in Support of Amphibious Operations

The fundamental phases the MCM systems must perform are the Exploratory, Reconnaissance, and Breakthrough phases to support an amphibious mission. The most critical tasks in accomplishing these objectives is identifying where the obstacles and mine fields are. However, unlike the mission to conduct MCM operations to protect sea lanes of communication or port security; the second most important task is clearing the mine fields. This concept is derived from several sources. A 1998 Concept for Future Naval Mine Countermeasures in Littoral Power Projection report stated:

> Rather than pursue an attritionist approach through cumulative destruction, the commander must subject the enemy's mines and obstacles to rigorous surveillance and reconnaissance in order to locate and avoid them altogether or maneuver through existing gaps. When avoidance is not an option and adequate gaps are not readily identifiable, rapid, in-stride breaching of the enemy's mines and obstacles will be conducted (Rhodes & Holder, 1998).

This was again echoed in a 2000 report from the United States Naval Research Advisory Committee (NRAC) Panel:

> The MCM mission must provide for mine clearance for checkpoints, straits, and the full length of the lines of communication as well as for projection of power ashore. There have been on-going evolutionary changes to doctrine and tactics that capitalize on the full potential of our current capabilities. These changes in tactics and doctrine have not solved the mine threat in the CLZ to 40ft water depth; however, the emerging tactics do offer an alternative of going around or over a mined beach. The commander must detect, classify and identify the construct of the mine threat, assess the viability of gaps, determine the potential for in-stride penetration and issue an operations order. The order might direct exploitation of the gaps, direct minefield clearance for surface assault, or order vertical envelopment, or any combination of the above, including all of them. The requirement to clear the mined area remains. The order must provide mine clearance of an area large enough in capacity to provide for the unloading of the huge volumes of materiel and warfighting personnel required to exploit the initial attack and conduct subsequent operations ashore… (Naval Research Advisory Committee, 2000).

Lastly, in a 2005 brief to the Mine Warfare Association, Brigadier General Neller stated, "Commanders must be able to detect and avoid mines when possible, and breach them when necessary" (Neller, 2005).

c. *Mine Clearance Area*

The most critical objective is finding the gaps during the reconnaissance phase of the operation. However, in order to determine the number of assets needed to conduct a MCM reconnaissance; the size of the area and number of routes needing reconnaissance must be determined.

Figure 8 comes from Brigadier General Neller's presentation to the Mine Warfare Association and it depicts the size and the number of routes needing reconnaissance for one Marine Expeditionary Brigade (MEB). From the figure, a MEB needs two littoral penetration sites (LPS) to land its assets ashore. A LPS is a continuous segment of coastline through which landing forces cross by surface or vertical means (STOM, 2011). It is an area big enough to support the landing of one Battalion Combat Team (BCT). However, to provide flexibility for the Marine force to maneuver from over the horizon, a MEB requires at a minimum 4 LPS to be reconnoitered. Each LPS will consist of 8 potential littoral penetration points (LPPs). LPPs are a spot on the shore to fix as objective for the amphibious force to breach or come ashore. It needs only be large enough to support the passage of a single craft, but it may be used by a maneuver element or series of maneuver elements passing in column (STOM, 2011). The BCT will actually need only 4 LPPs to be cleared, but once again requires the flexibility in maneuver. Therefore the MCM assets must be able to reconnoiter a total of 32 LPPs. If the amphibious operation needs to support 2 MEBs it could be surmised that the MCM operation must reconnoiter 64 LPPs and clear 12 to 16 LPPs.

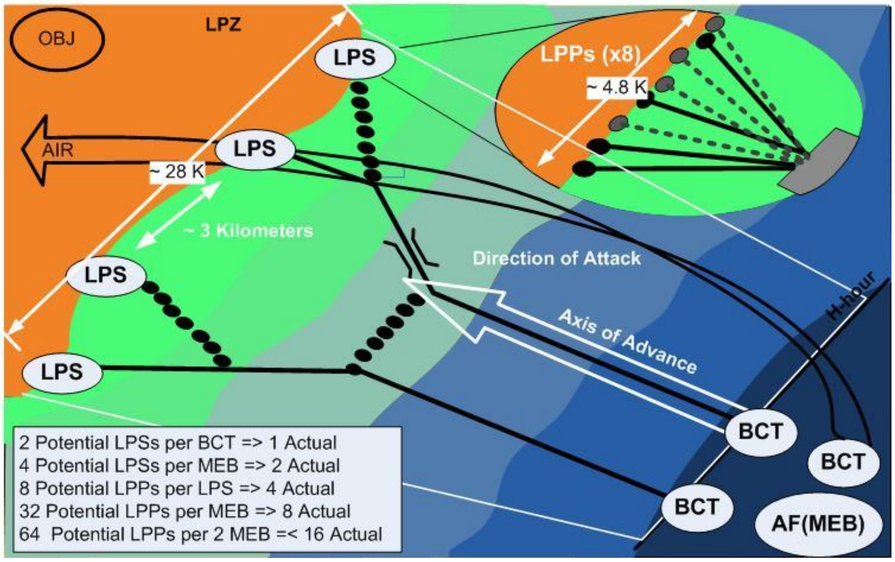

Figure 8. Amphibious Landing Site Dimensions

Map depicts the number LPPs and size of area that MCM assets will need to clear (Neller, 2005).

To determine the width of the area that needs reconnoitering, it is surmised that each LPP is wide enough to support one boat lane. A typical boat lane as described in MCWP 3-13, is between 2000 to 2700 yards long by 500 yards in width (MCWP3-13, 2005). Therefore if each LPP is 500 yards in width and they are separated by 100 yards, a LPS must be at a minimum 4800 yards in width. If each LPS is separated by 3 Km as shown in Figure 8, the minimum width for MEB landing site is approximately 28 Km. To support 2 MEBs, the landing site width can range from 28 to 56 Km. This is because the MEB could land side by side or one after another.

The length of the area is determined by adding the length of the boat lane with the approach lane. Figure 9 shows the concept for launching Amphibious Assault Vehicles including the approach lane, launch area and a boat lane. The approach lane is the area in which a boat approaches an area to launch AAVs. The approach lane typical length is from 2000 to 10,000 yards (MCWP3-13, 2005). Therefore the total length of MCM clearance area is the boat lanes plus the approach lane, which is a maximum of 12,700 yards. The maximum overall area the amphibious MCM assets must reconnoiter and clear to support an amphibious landing for 2 MEBs is approximately 56 Km by 12.7 Km.

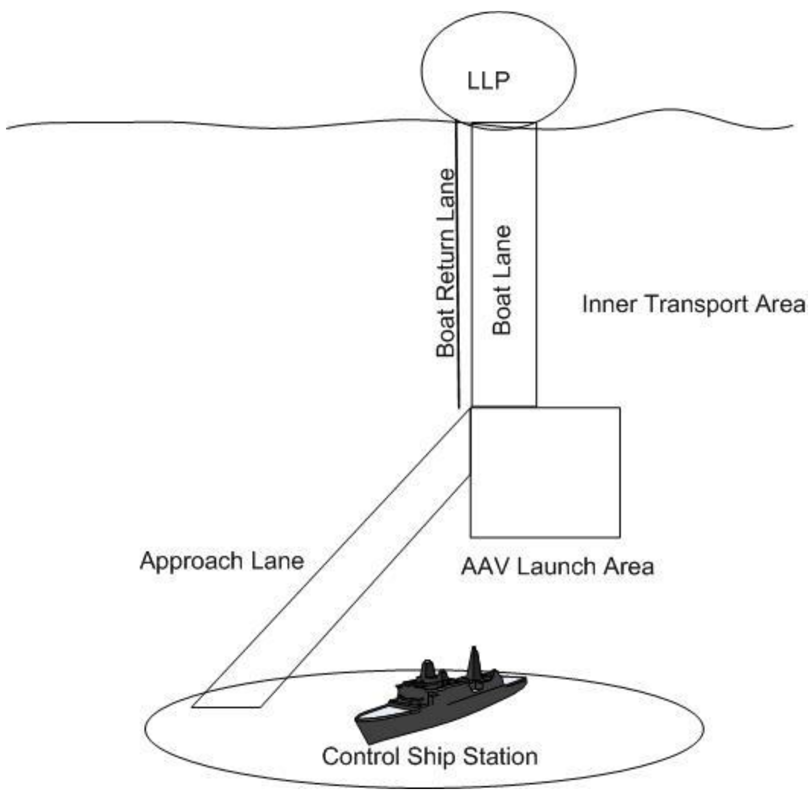

Figure 9. Amphibious Operations Area

Figure depicts the concept for launching AAV in support of an Amphibious Operation (MCWP3-13, 2005).

2. Current Mine Clearance Operations

If mine fields cannot be bypassed on certain lanes, breach operations become necessary. It is during the breakthrough phase, the third MCM operational phase, in which the ATF will perform breaching operations of the mine fields that cannot be bypassed or gone around. MCM doctrine states that there are 4 fundamental steps to breaching a mine obstacle in support of an amphibious landing which are: Suppression, Obscuration, Security, and Reduction (Joint Pub 3-15, 1999). Alternatively, NATO describes these steps as: Suppression, Obscuration, Isolation, and Reduction (NATO, 2010). For the purpose of this report, the NATO doctrine will apply. NATO document ATP-8(B) Volume I describes these steps as the following:

a. Detection of a Minefield

The mine field is detected and classified by the ATF during the exploration and reconnaissance phase shown in Figure 10. Boat lanes are determined and mines needing neutralization are selected.

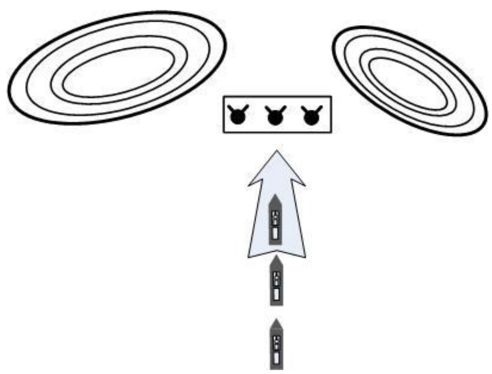

Figure 10. Mines are detected and located

Drawing depicts a naval force approaching a mine obstacle between two islands.

b. Suppression

"Effective suppression is the mission-critical task during any breaching operation. Suppression protects the forces that are conducting operations to reduce the sea mine risk, neutralize obstacles or maneuver through these, and fixes the opposing force in his position. Suppressive fires include the full range of lethal and non-lethal fires, from naval gun support (NGS) and close air support (CAS) to electronic attack (EA)" (NATO, 2010). Figure 11 graphically shows a concept for suppressing the threat's ability to over-watch the mine field.

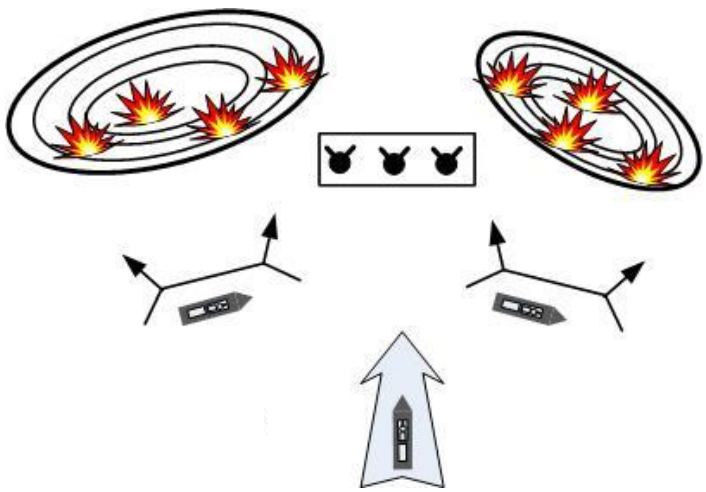

Figure 11. Suppression of Threat

Drawing depicts a naval force providing suppressive fire for the commencement of mine obstacle clearing.

c. Obscuration

"Obscuration hampers opposing forces' observation and target acquisition (TA), and conceals friendly activities and movement. EA prevents the opposing force's use of radar and radio signals to observe and report the operation" (NATO, 2010). Figure 12 demonstrates a naval force that is obscuring the mine field with smoke, suppressive fire, and electronic jamming.

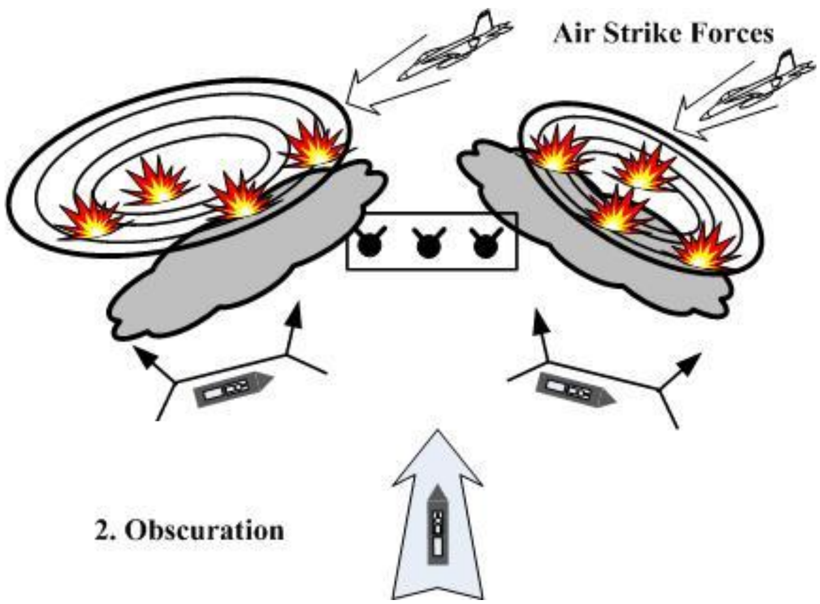

Figure 12. Obscuration

Drawing depicts a naval force providing suppressive fire and obscuration for an MCM force to clear a mine obstacle.

d. Isolation

"Isolation of the landing area is required to prevent opposing force interference with (sea) mine and obstacle clearance operations, and passage of forces ashore through breached lanes. Isolation can be achieved in a manner similar to that described in Suppression and also by elements of the landing force that are placed ashore by air-insertion. These landing force elements can neutralize coastal defense installations and seize and deny routes of ingress into the landing area, thus preventing the opposing force to counter-attack the landing beaches" (NATO, 2010). Figure 13 demonstrates the amphibious force isolating the coastal defense from being reinforced and being able to engage the MCM force.

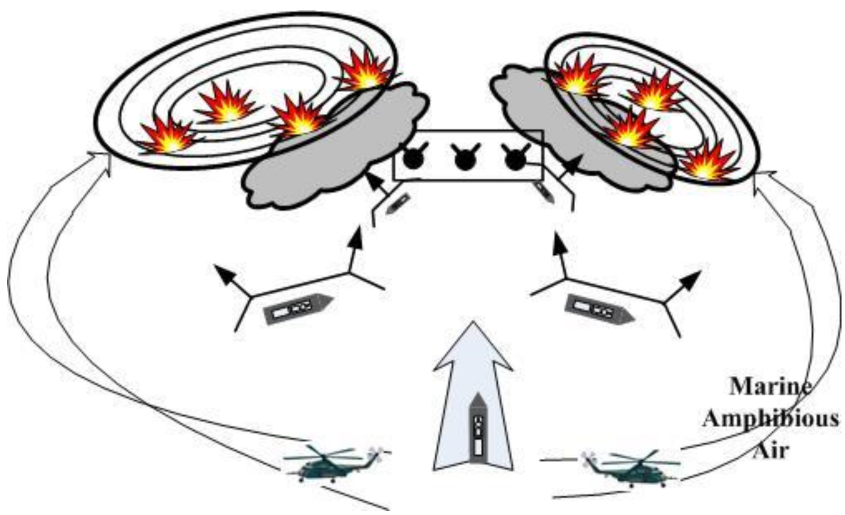

Figure 13. Isolation

Drawing is to demonstrate a naval force providing suppressive fire, obscuration and isolating the threat from the mine obstacle.

e. Reduction

"Identification and marking of safe lanes for the landing force to conduct surface landings takes place by naval forces from the ATF, other assigned forces, and elements from the landing force. The location of lanes depends largely on identified weaknesses in the sea mine and obstacle belt. If the ATF cannot find gaps or weak coverage in the obstacles, they will apply concentrated force at a designated point to rupture the defense and create a gap. Units reducing obstacles mark the lane and report the obstacle type, location, and lane locations to higher headquarters. Details of lanes are handed over to follow-on forces that further reduce or clear the obstacles, if required" (NATO, 2010). Figure 14 demonstrates the time when the MCM force has successfully reduced the mine obstacle and has created a breach for the amphibious force to transit through.

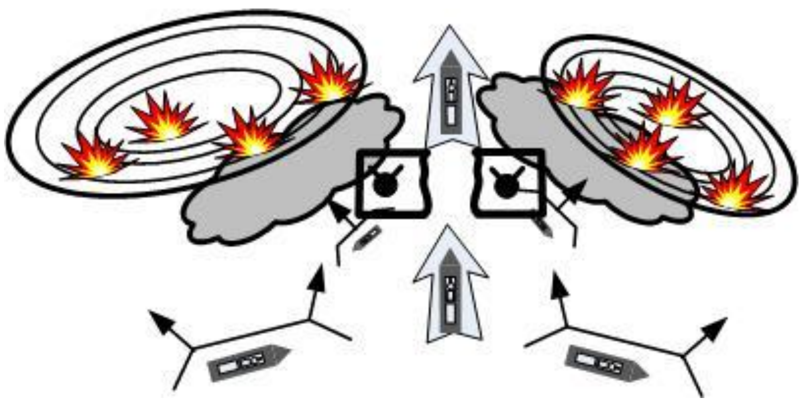

Figure 14. Reduction of Obstacle

Drawing is to demonstrate a naval force breaching and reducing the mine obstacle to allow the naval force to pass.

3. **Analysis of Capability Gaps**

In order to understand and appreciate the capability gaps for current MCM operations supporting an amphibious force, a comparison analysis was conducted evaluating previous amphibious landings with current and expected future US Naval assets. Even though there are more recent historical examples of amphibious operations, the WWII invasion of Guadalcanal was chosen for comparison to a hypothetical invasion with today's and future naval assets for the following reasons:

1. Guadalcanal was the first invasion for the United States during WWII. This created a situation in which the US tested its newer technology and tactics for conducting amphibious operations against an enemy with a coastal defense. The application of new technology and tactics is still relevant to amphibious force landings today.

2. Two crucial battles had taken place before Guadalcanal, the Battle of Coral Sea and the Battle of Midway. This made the US and Japan on parity for Air and Naval operations. The US did not hold air superiority, nor did its naval forces have a superior advantage over Japan. This would be the case today if the US would experience a conflict with China or Russia and it needed to perform an amphibious operation.

The full comparison analysis is contained in Appendix C. The following capability gaps were found through the comparison analysis and current doctrine.

a. OTH Capability

The use of Anti-Ship Cruise Missiles (ASCM) by a defensive force necessitates sufficient standoff distance by the invading force in order to avoid and counter the ASCM threat. The presence of ASCMs drives the requirement for the ATF to operate from OTH. OTH is a difficult term to define as the definition of the appropriate OTH distance from the objective varies. Joint Publication 3-02 Amphibious Operations states that "over-the-horizon amphibious operation is an amphibious operation initiated from beyond visual and radar range of the enemy shore" (JP 3-02, 2009). This is normally at the horizon which is approximately 22 to 25 miles at sea. However, it is suggested that the ATF that contains MCM assets initially operate no closer than 50 nm from the objective in order to provide a large margin of time to react to launched ASCMs. Additionally, other analysts have said that amphibious assaults will be launched from OTH at 25 to 50 miles at sea (Committee on Naval Expeditionary Logistics, 1999). This further justifies that current and future MCM system should have the ability to be deployed and launched from distances greater than 50 nm in order to meet the highest requirement.

b. MMS and need for Unmanned Vehicles

MCM Operations from distances greater than 50 nm creates other gaps in MCM system performance. It drives the need for unmanned vehicles to replace the divers and MMS to perform MCM operations for the amphibious force. According to stakeholder inquires, the MCM operations must be done within a 48 to 72 hour time frame before the arrival of the main Task Force (TF). This drives a requirement for a capability of sustained covert MCM operations to be done at distances greater than 50 nm from the C2 ships. Even though MMS can be inserted covertly, the sustaining covert operations at distances greater than 50 nm from C2 ships starts to exceed marine mammal limits, and can be considered a deficiency in the capability to perform the mission.

c. Communication Gap with Unmanned Vehicles

MCM operations from distances greater than 50 nm creates a gap in the ability to communicate with remote vehicles. The MCM system will have a need for a secure, adaptable,

and robust communication system. Taking into consideration that many communication systems are line-of-sight (LOS) systems, C2 MCM ships operating at distances 50 nm or more from the objective will be unable to communicate with distant remote vehicles. The MCM C2 ships will require another method to communicate with the unmanned vehicles, and possibly use multiple communication methods and connections to respond to failures or dropped connections to maintain communication when transiting through and about the operation area.

d. System Manning Gaps

In addition to the system need for adapting to communication modes, there are other circumstances that create the need for a capability to operate autonomously. Presently, MCM personnel are estimated to number 690 personnel from calculations for MCM Sea and Air support. This estimate is based on the fact that it takes 6 officers and 75 enlisted to operate an MCM ship. If 25% of the crew is used to run the ship and the other part is used to run the MCM systems; then it requires 60 personnel for the MCM assets. Task Force 76 (TF 76) is a forward deployed Pacific force consisting of Amphibious Squadron 11 and a Mine Countermeasure Squadron. TF 76 is composed of 4 MCM ships, which equates to 450 MCM personnel to support a given mission (Task Force 76 Webmaster, 2011).

The Navy started retiring MCM class ships in 2008, planning to have their mission fully taken over by the LCS in 2017 (Munoz, 2011) when all MCM class ships have been decommissioned. The LCS will have only 35 additional berthing accommodations for mission kit personnel (O'Rourke, 2011). If each LCS shown in Table 42 (Appendix C) was dedicated to MCM operation, this equates to 140 berthing spaces available. However, it is not reasonable to assume that all four LCS are dedicated to MCM. It should be assumed that one of the LCS will be dedicated to Anti-Submarine Warfare (ASW) to protect the landing force. Therefore, the total berthing dedicated to MCM will be about 105. A future MH-60 AMCM detachment (DET) will consist of 23 personnel. If two AMCM DETs are attached to the LCSs then there will be a requirement to provide berthing for 46 personnel. This leaves room for 59 personnel to support the surface MCM operation as compared to the 450 for present day missions.

In a meeting discussing remote piloted aircraft (RPA), the chief scientist for the US Air Force, Dr. Mark Maybury, said that the “Number 1 manning problem in the Air Force is manning our unmanned platforms” (Maybury, 2011). Dr. Maybury showed RPAs need just as many, and sometimes more personnel to operate than piloted vehicles. The Air Force and Army recognize that the answer to reducing the number of required personnel and the life-cycle cost of remote piloted vehicles (RPV) is the creation of autonomously operating unmanned vehicles. The Navy is currently creating ships with lower personnel capacity, but that creates gaps in the ability to command and control remotely piloted vehicles. The reduction in future manning

requires MCM vehicles to operate with autonomy so that the manning requirement is reduced. The MCM vehicle needs not only the capability to operate in a fully autonomous mode, but in a semi-autonomous mode to provide mission-dependent options and redundancy of control.

Understanding how to solve current and future manning constraints starts with defining current manning expected for MCM systems, especially in the case of the MK 18 Mod 1 UUV systems. This has proven to be difficult to define since on station manning depends on the experience and proficiency of the current trained operators and the size of the mission. At this point, assumptions have been determined based from stakeholder information that typically, the mission will consist at a minimum of 7 personnel: two UUV operators that handle system launch and recovery and operations, one qualified small boat operator, and two Post Mission Analysis (PMA) personnel to review the collected and processed data. The number of personnel required for the mission expands in respect to the size of the mission area increasing. This would then require additional UUVs, UUV operators and PMA personnel, especially if additional vehicles are required to be launched with more complex sensors that are expected to produce large amount of imagery data to be reviewed.

e. Unmanned Vehicle with On-Board Processing Gap

Many present day MCM unmanned vehicles need to be recovered to download information so that human post mission analysis (PMA) can be performed on the collected data. Stakeholders have indicated that PMA is error-prone, produces false positives, and is a very lengthy process. This alone drives a requirement for the MCM vehicle to have the ability to perform its own processing with reliable auto-target recognition (ATR) functions. However, with the requirement for the MCM system to operate further than 50 nm from the C^2 ships, the MCM vehicles will not be able to transition back-and-forth between the C^2 ships and the AO without taking up precious mission time and resources. This creates another gap in being able to perform the MCM mission. The MCM system must have the capability to perform on-board processing and compress the information and conduct data transmit and receive effectively to the ATF without delaying mission execution.

f. Unmanned Vehicle Deployment Gap

Covert MCM operations from distances greater than 50 nm also creates a need for the MCM vehicle to be delivered covertly to the AO. Presently there are no MCM systems being developed that can be delivered via stealth at distances greater than 50 nm. MCM vehicles should be capable of being delivered or deployed from subsurface, air, stealthy surface, or ordinance delivered platforms. Additionally, since the distance between the AO and where the C^2 ships are located are so great, the MCM vehicles need a high degree of endurance to transit and operate for long periods of time. This is outside the ability of most MCM systems today.

Future MCM vehicles will need the capability to be covertly and autonomously be refueled or recharged to sustain their operation. They should be able to loiter and conserve energy while not performing a mission or waiting to be recovered.

g. VSW Sensor Gap

As discussed earlier, the VSW region is difficult to operate in as it suffers from merging Ekman boundary layers, transient stratification, buoyancy fluxes caused by changes in salinity of the water, and various winds, waves, tides, and currents (National Academy Press, 2000). This drives the need for MCM vehicles that operate in the water with strong propulsion system with precise and robust navigation and sensor systems. Currently there are no water-borne systems that can operate effectively in all environmental conditions in this region today. The ability to design systems to perform in the diverse VSW environment still remains a gap in the ability to perform MCM for an amphibious force.

The diverse quality of the VSW region makes it impossible to use just one sensor to detect, locate, and classify mines. Waves and winds can change the optical and acoustic properties of water columns due to circulation caused by the influence of local coastal topography (National Academy Press, 2000). Local weather can cause conditions that produce muddy, outflows of water from nearby rivers and estuaries. The fluid dynamics can quickly cover and uncover mines by shifting the sea floor. Euphotic zones, caused by organic and inorganic materials dissolved or suspended in the water, will degrade optics and lasers. The sound reverberation backgrounds, low signal-to-noise environments and high cluttered acoustic backgrounds will degrade acoustic sensors (National Academy Press, 2000). Lastly the dumping of metal clutter, shipwrecks, and fishing losses will produce false positives with magnetic detectors.

Most MCM systems are single sensor systems which do not collaborate with other systems. This creates a gap in the ability to perform effective MCM operations in the VSW area with unmanned systems. The MCM system must have the capability to fuse information from multiple sensors and process it to detect, locate and classify mines.

h. Neutralization Gap

Lastly, there are no unmanned MCM systems that effectively perform neutralization (disable a mine) in the VSW area. There are no systems being developed that can be deployed from OTH and can be used to covertly neutralize mines. This creates another gap in our ability to perform amphibious assaults against a hostile force with an anti-landing defense. There is a need to develop a neutralization system that will either neutralize the mine covertly or neutralize it on command.

D. STAKEHOLDER ANALYSIS

A stakeholder analysis was conducted to identify stakeholder needs, requirements, scenarios, modeling metrics and parameters, and input for system benefits, cost, and trade-off analysis. Questions posed to stakeholders in the analysis were derived from research and stakeholder documents pertaining to the problem statement.

1. Objectives

The objective of the stakeholder analysis was to identify applicable stakeholders, gather background details about MCM, and develop a summary of their needs. Research was conducted utilizing the stakeholders' own MCM documentation and public MCM literature to find answers and information, and to clarify specific questions relating to the problem at hand. The process used for conducting the stakeholder analysis is shown Figure 15.

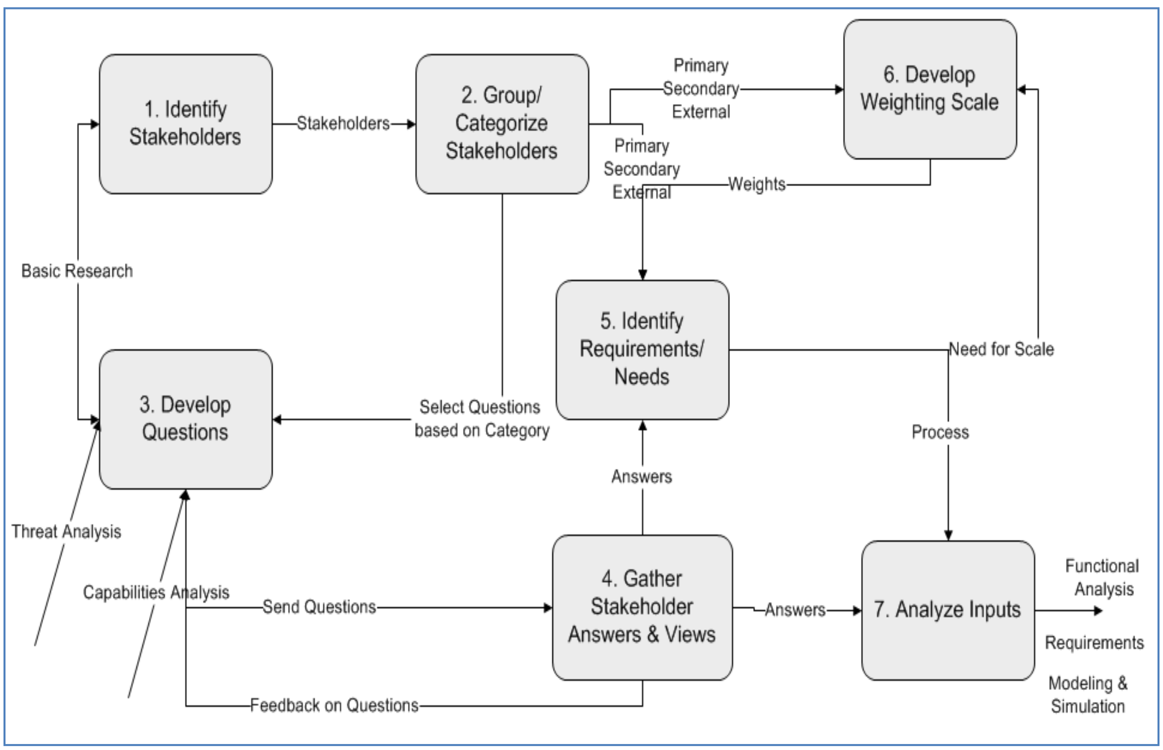

Figure 15. Stakeholder Analysis Process

Stakeholder Analysis Process used in elicitation of input from stakeholders and translation of input to requirements.

The stakeholder analysis consisted of performing seven different activities: Identify Stakeholders, Group/Categorize Stakeholders, Develop Questions, Gather Stakeholder Answers & Views, Develop Weighting Scale, Develop Process to Identify Requirements/Needs, and Analyze Inputs. Further descriptions of these activities are detailed as follows:

a) The first activity, Identify Stakeholder, conducted an analysis of resources used to date in order to identify stakeholders. This activity served as an input to conducting basic research. During this activity, contact with stakeholders was initialized by requesting them to communicate with our group about MCM. The output of this activity was a list of potential stakeholders.

b) The second activity, Group/Categorize Stakeholders, grouped and categorized the stakeholders into three groups: Primary, Secondary, and External.

    a. Primary Stakeholders consisted of stakeholders who are held responsible for success or failure of the system.
    b. Secondary Stakeholders consisted of stakeholders that had a large stake in the system and had a high profile but were not directly held responsible for success or failure of the system.
    c. External Stakeholders consisted of stakeholders that were affected by the system but had very little if any input or involvement in implementing the solution.

   During this activity the stakeholders were evaluated for the relevancy to the project. If the identified stakeholders did not fall into one of these groups they were deleted. The output of this activity was three stakeholder groups.

c) The third activity, Develop Questions, drafted potential questions to discuss with stakeholders based on the capstone project problem statement. Questions were generated from the external activities of the basic research, the threat analysis, and the capabilities analysis, coupled with initial feedback from stakeholder interaction. Questions were selected and categorized for individual stakeholders based on the output of activity 2, the relevant grouping or categorization of stakeholders. The output of this activity was a set of questions that were e-mailed or personally discussed with stakeholders.

d) The fourth activity, Gather Stakeholder Answers & Views, gathered and sorted the resulting answers and opinions from stakeholders from the third activity, Develop Questions. The stakeholder answers were assessed to determine if a process needed to be developed to identify and discriminate between conflicting viewpoints. The output of the Gather Stakeholder Answers & Views activity resulted in a master list of responses from the stakeholders.

e) The fifth activity, Identify Requirements or Needs, developed a process for de-conflicting different viewpoints from the stakeholders. This process was used to filter responses and to identify and prioritize requirements and needs. The Identify Requirements/Needs activity took the outputs of activity 2, Group/Categorize Stakeholders, and activity 6, Develop Weighting Scale, to develop a process for evaluating answers. The Identify Requirements/Needs activity was triggered by the responses of the answers gathered

from the stakeholders (activity 4). If the answers did not warrant a formal process, this activity was skipped.

f) The sixth activity, Develop Weighting Scale, developed a weighting scale based on the category of stakeholders. The weighted scale allowed the stakeholders that are most closely related to the problem to have precedence in the decision-making process. This activity was triggered by the output of activity 5, Identify Requirements/Needs. If there was a need to develop a formal process to evaluate the answers, this activity created stakeholder weights.

g) The last activity, Analyze Inputs, took the stakeholder answers from activity 4, Stakeholder Answers & Views, and translated them into requirements, capabilities, and scenarios for modeling. This translation was accomplished by intuitive analysis of the answers or via the filter created by activity 5, Identify Requirements/Needs. The output of this activity was fed into the external activities of modeling, requirements development, and the capability analysis.

2. **Stakeholder Identification**

Table 5 contains the list of stakeholder organizations that were identified in this Capstone Project. Personnel identified in the list are representatives of the stakeholder organization.

Table 5. Stakeholders List

Stakeholder organizations identified to have an interest in Next Generation Mine Countermeasures in the VSW zone in support of Amphibious Landings. Personnel identified in the list are representatives of the stakeholder organization.

Stakeholders					
Organization Code	Organization Title	Person	Primary	Secondary	External
PMS 403	Remote Mine hunting Systems Program Office	Mr. Steven Lose	X		
PMS 408	Explosive Ordnance Disposal (EOD) and Counter Radio Controlled Improvised Explosive Device Electronic Warfare (CREW) Program Office	Mr. Matt Zalesak	X		
PMS 420	Littoral Combat Ship (LSC) Mission Modules Program Office	Mr. George B Saroch	X		
PMS 495	Mine Warfare Systems Program Office	Mr. Andrew Fuller	X		
PMA-299	H-60 Program Office	Mr. Danny Sinisi	X		
OPNAV - N852	Mine Warfare Branch	LCDR Brian Amador	X		
NSWC-PCD	NSWC Panama City Division - Mine Warfare Systems Branch	Mr. Aamir Qaiyumi	X		
OPNAV-N88	Director, Air Warfare Division	CDR Shelby Mounts		X	
OPNAV-N880	Aviation Plans and Requirements			X	
PMS 340	Navy Special Warfare Program Office			X	
USMC-CmdEng	USMC Combat Engineering	Capt Peter Moon			X
NMAWC	Naval Mine and Anti-Submarine Command	Mr. Marvin Heinze	X		
EODMU 1	Explosive Ordnance Disposal Mobile Unit 1	LCDR John Schiller Executive Officer EODMU 1	X		
EODMU1	ITT Tech Rep	Mr. Matt Clements	X		
EODMU1	ITT Tech Rep	Mr. Bob Stitt	X		

3. Stakeholder Interviews

Appendix B lists the questions that were developed from stakeholder research and the answers that provided input into the threat and capabilities analyses. Stakeholder questions were directed at the relevant stakeholder, as indicated, with the resultant response or non-responses. The questions varied in topics from the stakeholders' perspective of current system performance to asking stakeholders to identify current MCM capability constraints. When stakeholders were asked to address if current systems today are capable of removing the man/MMS from the mine field, it was an unanimous agreement that current systems are not providing this capability and are still requiring nearby support.

When stakeholders were asked to address current operational constraints imposed in current MCM operations and systems, the stakeholders all gave different, but all valid concerns. One stakeholder indicated that the diversity of the VSW environment and our ability to develop technology to perform in all situations was a constraint for conducting operations. Another stakeholder identified that large current system footprints are a major constraint and are limiting MCM deployment capabilities. An additional constraint came from a stakeholder who voiced that current doctrinal restrictions of identification and classification by a human (diver) and confirmed to be officially classified and also before neutralization can occur is something that potentially inhibiting the advancement of technology solutions.

Not all questions were able to be answered or were answered in general terms in order to avoid discussions into classified areas. Some questions related to platform interoperability with the LCS or future MCM platforms were not answered, as well as questions related to current amphibious lane clearance marking methods. Some of the vague answers were related to questions about future manning expectations with responses that were very short and limited. Stakeholders did indicate what questions they currently did not have answers for varied from questions related to future manning concerns and various future operational considerations.

4. Stakeholder Analysis Summary Findings

At the conclusion of the stakeholder analysis, the number one insight discovered was the apparent disconnect between the MCM community and the Marine/Navy Amphibious Operations strategic planning activities.

Additional key points from the stakeholder analysis are:

a) As the MCM-1 decommissioning process is being executed, the replacement surface-based MCM systems will need to be housed and stored on the new Littoral Combat Ships

(LCS) or other amphibious ships. There seems to be a lack of coordination in defining shipboard manning and footprint requirements for the MCM equipment and personnel.

b) The most effective system for performing MCM in the VSW region is the Marine Mammal System (MMS). However, their footprint is extremely large, consuming the majority of amphibious ship well deck. This is precious space that would normally be dedicated to Marine Corps personnel and equipment.

c) The Marine Corps requires that MCM must provide the capability to clear a minimum of 12 boat lanes to land 2 Marine Expeditionary Brigades (MEBs) of 29,000 Marines and Sailors (Trickey, February 2010). The requirement is for the lanes to be cleared covertly within the objective of 72 hours. There appears to be a lack of planning for the number of assets required by the MCM force to facilitate the clearance of those lanes or a timeline for conducting clearance operations. The MCM community does not accurately address the amount of time it will take to collect the data, recover the data, and perform the clearance supporting an amphibious force.

d) All Unmanned Underwater Vehicles (UUVs) require a launch and recovery platform that is typically a small craft that remains close to the minefield. At this point, UUVs support removing the diver from conducting clearance operations but it does not support stakeholder requirements of removing the man from the minefield.

e) All the systems being developed presently to replace the MMS require post mission analysis (PMA) to be performed. Man/Mammal replacement systems are increasing the DTE timeline because there is not currently an efficient way to gather real-time data from the UUV platform.

f) PMA currently involves humans manually reviewing several hours of sonar data which is time consuming and error prone due to human fatigue.

g) All the systems currently under development are tested and operated with the assumption that the environment is permissive. This is an unrealistic expectation in performing an amphibious operation, and it should be assumed that operations will be in non-permissive, hostile environments. MCM systems need to be designed to counter anti-landing defenses. Anti-landing doctrine focuses on the development of four layered barriers and the particular area that the MCM community should be concerned with is the engineering barriers. Doctrine emphasizes that the engineering barrier will be over watched by land based artillery, air-defenses systems and crew served weapons (JP 3-02, 2009). The enemy threat intends to deny freedom of movement to conduct MCM operations. The MCM scenarios for the development of MCM systems revolve around a port defense or clearing a Q-lane. It should be expected that the enemy who has planted mines for an anti-landing defense will have an over watch that will engage the MCM force upon detection with direct and indirect fire.

h) Systems being developed do not fully address Over-the-Horizon (OTH) amphibious operations. An assumption made for this analysis is that the MCM community is focusing on getting initial concepts and technology to work in the challenging VSW environment, rather than focusing on the need for clandestine MCM operations needed to support OTH capabilities.

i) MCM clearance execution is not consistent with training execution. In training, divers and MMS train to complete full DTE operations. In execution of real world events, the mission is often cut short and a full DTE is not always complete. An assumption made for this finding is that due to the timeline restrictions, the execution of neutralization is very rarely performed.

j) In the MCM systems in use today and under development for the future, there is limited UUV neutralization capability. From informal discussions with PMS 408 (EOD), it was indicated that only recently, development of a UUV mine neutralization system, the EUNS (Expendable UUV Neutralization System), has begun with notional concept development. The lack of neutralization assets creates a situation in which MCM and amphibious forces must perform a mark and avoid maneuver. However, it was not indicated from the research about how mines will be marked or their locations communicated to a Marine Corps force performing OTH amphibious operations.

k) In technology demonstrations, there are usually several different UUVs completing separate missions. Each technology team runs portions of the mission profile and limited time is focused on running them together as a complete DTE sequence. MCM has not fully analyzed how these assets will be coordinated or controlled as an MCM SoS in support of Marine Corps amphibious operations.

5. Stakeholder Analysis Conclusion

From the stakeholder feedback received, it was clear that there are no current or emerging solutions that can accomplish the full DTE mission. The lack of response from a number of critical stakeholders, limitation on some information due to content classification, and conflicting responses as indicated in Appendix B prompted an informal analysis of responses detailed in the previous section. This informal analysis of the information received seems to reveal an emerging disconnect between the Mine Countermeasure (MCM) community and the Marine/Navy Amphibious Operations planning elements.

This disconnect could be caused by a number of reasons. One assumption made from this analysis is that MCM architecture should be considered a system of system (SoS). It is composed of several systems consisting of ships such as the Littoral Combat System (LCS), helicopters such as MH-60S and MH-53E, divers, Marine Mammals Systems (MMS), Light

Detection and Ranging (LIDAR) systems, air and sea acoustic and magnetic systems, recording and post mission analysis systems, and delivered and air delivered neutralization systems. In addition to the multiple stakeholders and systems involved in the triad of MCM clearance, MCM architecture should be considered from a SoS approach due to the complexity and diversity of the VSW environment. It is recommended as a potential solution to use multiple vehicles that individually conduct smaller portions of the DTE sequence. This approach is also recommended that the SoS takes into consideration full collaboration throughout the mission to conduct MCM operations in order to ensure that system requirements and functions are met.

On future amphibious ships and LCS platforms, there will be limited transport space and available berthing for support personnel. The systems currently being developed span a number of different organizations and contractors that do not seem to know how they are affected by the other organizations with similar missions, or what requirements are levied on them from other organizations' decisions. These organizations referenced in Appendix B,

Table 5 are focused on their own development and have not communicated with each other sufficiently to meet the needs of the Navy/Marine Corps customer. A hypothesis is that there is a need for a Lead System Architect for the overall MCM SoS. However, the results of this stakeholder analysis did not give enough supporting evidence from critical stakeholders to confirm or deny this hypothesis.

Future systems will be able to conduct port defense, sea lane protection and clearance in a permissive environment. However, the systems that are currently fielded or being developed have severe limitations in supporting a marine amphibious operation against anti-invasion defense. If these disconnects are not corrected, marine amphibious operations will be severely handicapped.

The disconnection seems to be with the MCM community concentrating on developing systems that require platforms to have freedom of launch, recovery, and operation without considering entry and operation in denied access areas. The presentations and training of these systems appear to assume the MCM unit has freedom of movement and the ability to operate from land. This will not be the case when performing amphibious landings against a threat that has an anti-invasion defense.

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III. SYSTEM DEFINITION

A. IMPORTANT NEXT GENERATION CAPABILITIES

Based on the analysis of gaps in existing and planned systems against current threats, operational considerations, and the results of the stakeholder analysis, the following are the most important capabilities that are needed for the Next Generation Mine Countermeasures for the VSW Zone in Support of Amphibious Operations:

1. Covert Activities

The MCM system needs the capability of performing MCM operations covertly by maintaining a minimum visual, radar, magnetic, and acoustic signature to support the amphibious advance party activities. Covert operation will result in relaxing the need to provide suppression fire in the obscuration activity of the MCM breakthrough phase. If MCM can be conducted without detection, the opposing force will not react hostilely and expose forces to unnecessary risk.

2. Real-Time Information

The MCM system needs the capability to provide Marine amphibious forces with real-time information of mines and mine field locations, cleared and marked boat lanes, location of barriers, and outside disturbances and to allow the Amphibious Force to exploit gaps in enemy defense or avoid mine obstacles. This will give the Marine amphibious force the ability to employ Ship-To-Objective Movement (STOM) to outflank or envelop an adversary, secure the vulnerable flanks of other friendly forces, or to remove landward threats to the maritime domain (Marine Corps Development Command, 2011).

The MCM system's speed during the conduct of the mission, applies not only to the speed at which MCM platforms can cover a threat area, but also to the speed of data exchange, processing and fusion of information to give the Marine Amphibious force as significant advantage (Bachkosky, et al., 2000).

3. Rapid Clearance of Mines

The MCM system needs the ability to rapidly clear multiple boat lanes to allow the Marine Corps the ability to exploit flexibility, speed, and maneuver across domains.

4. Detection of Marked Mines

The MCM system needs the capability to effectively bottom map, assess the environment, detect, identify mines from non-mine bottom objects (NOMOs), classify mine

types, and mark and map mine locations with a high degree of certainty in the VSW to the beach exit to enable maneuver forces to avoid or bypass mines (Bachkosky, et al., 2000).

5. Over-the-Horizon Deployment

The MCM assets must have the capability of being deployed from OTH (50 nautical miles or greater). As discussed earlier, this gives the amphibious force the capability to offset the enemy's ability to target and react to the amphibious force with coastal defenses.

6. Autonomous Operations

The MCM system needs the capability to perform autonomous collaborative operations to reduce the manpower footprint to conduct MCM operations.

Autonomous vehicles are needed so that they can operate with future reduced manning requirements. Today's iteration of unmanned systems involves a high degree of human interaction. DoD must continue to pursue technologies and policies that introduce a higher degree of autonomy in order to reduce the manpower burden and reliance on full-time high-speed communications links while also reducing decision loop cycle time (Unmanned Systems Integrated Roadmap FY2011-2036, 2011).

For unmanned systems to fully realize their potential, they must be able to achieve a highly autonomous state of behavior and be able to interact with their surroundings. This advancement will require an ability to understand and adapt to the environment, and the ability to collaborate with other autonomous systems, along with the development of new verification and validation (V&V) techniques to prove the new technology does what it should.

Efficiencies can be gained by automating the tasking, processing, exploitation, and distribution (TPED) of data collected by unmanned systems. Autonomy can help extend vehicle endurance by intelligently responding to the surrounding environmental conditions (e.g., exploit and avoid currents) and appropriately managing onboard sensors and processing (e.g., turn off sensors when not needed).

7. Precise Navigation

The MCM system needs the capability for precise navigation, which allows for a common tactical picture and provides for safe navigation, mine avoidance, and reacquisition if necessary for neutralization purposes.

8. Sufficient Power and Propulsion Capabilities

The MCM system needs the capability that gives power of sufficient capacity to support propulsion and combat systems (sensors, onboard computer, communications, and neutralization systems).

The rapid development and deployment of unmanned systems has resulted in a corresponding increased demand for more efficient and logistically supportable sources of propulsion and power. In addition to improving system effectiveness, these improvements have the potential to significantly reduce life-cycle costs.

9. Robustness and Durability

The MCM system needs to be robust and durable in order to perform reliably in a hazardous environment.

10. Reduced Footprint

The MCM system needs the capability that gives it a vehicle footprint reduced to the degree that technology can allow to facilitate handling and flexibility with respect to transportation and deployment.

The stakeholder analysis documented that mammal systems can take up to a half of a well deck of an amphibious ship. With the retirement of the MCM ships, and reduced capacity in ship types, the physical footprint of MCM equipment must be reduced to allow other mission-essential equipment to be onboard to protect the amphibious force.

11. Easy Launch and Recovery

The MCM system needs the capability of a rapid launch and recovery. The man-machine interface must be designed to allow the MCM ATF to quickly put the MCM system into operation in order to reduce the DTE time frame.

12. Training

The MCM system must be designed for training capabilities that can be assessed against joint training requirements. Such a strategy will improve basing decisions, training standardization, and has the potential to promote common courses resulting in improved training effectiveness and efficiency.

13. Interoperability

To achieve the full potential of unmanned systems, the MCM system must be capable of operating seamlessly across the domains of air, ground, and maritime and also operate seamlessly with manned systems.

Robust implementation of interoperability tenets will contribute to this goal while also offering the potential for significant life-cycle cost savings. System interoperability is critical in achieving these objectives and requires the implementation of mandated standards and Interoperability Integrated Product Team (I-IPT) profiles. Properly implemented, interoperability can serve as a force multiplier, improve joint war fighting capabilities, decrease integration timelines, simplify logistics, and reduce total ownership costs (TOC). One of the most powerful tools in maximizing interoperability and achieving these objectives is the adoption of the open systems architecture concept (Unmanned Systems Integrated Roadmap FY2011-2036, 2011).

14. Communications

Unmanned systems rely on communications for C2 and dissemination of information. The MCM system design should be capable of addressing frequency and bandwidth availability, link security, link ranges, and network infrastructure to ensure availability for operational/mission support of unmanned systems. The MCM system should be capable of transmitting and receiving command and control information underwater.

Planning and budgeting for Unmanned System operations must take into account realistic assessments of projected satellite communication bandwidth, and move toward onboard pre-processing to pass only critical information. Additional benefits are greatly reducing high bandwidth communication needs and decreasing decision cycle time.

B. DESIGN REFERENCE MISSION

To assist with the development of system requirements and to compare potential system architectures that would improve effectiveness of mine countermeasures in relevant operational situations, a DRM was created. The DRM takes into account current MCM and amphibious landing doctrine in developing a realistic situation to test the viability of potential MCM system architectures.

1. DRM Objectives

OBJECTIVE 1. The overall objective for this DRM was to develop scenarios to help determine the feasibility of an MCM system supporting an amphibious operation within a threshold of 72 hours and an objective time of 48 hours after deployment.

OBJECTIVE 2. Define area coverage rates (ACR) in the VSW area for the following:

a. Detection of mine field
b. Location and classification of mines
c. Mapping of mines/obstacles and gaps
d. Neutralization of selected mines

OBJECTIVE 3. Explore communication effectively between MCM system, Assault Force (AF), and Amphibious Landing Force (LF) during the mission profile.

OBJECTIVE 4. Provide insights and suggestions for changes in tactics based on information gathered from Objectives 1 through 4.

2. Concept of Operations

The MCM system is typically deployed by an AF arriving approximately 72 hours before the main body of the LF. The AF’s function is to participate in preparing for the main assault by conducting such operations as MCM (JP 3-02, 2009). To support the amphibious operation, there are three critical objectives the MCM force must accomplish as part of the concept of employment: exploratory, reconnaissance, and breakthrough (JP 3-15, 2011). Figure 16 shows a concept for the activities of the deployment and operation of the MCM system in accordance with Marine Corp doctrine. For this project the system will be bounded to the activities involved in the DTE sequence.

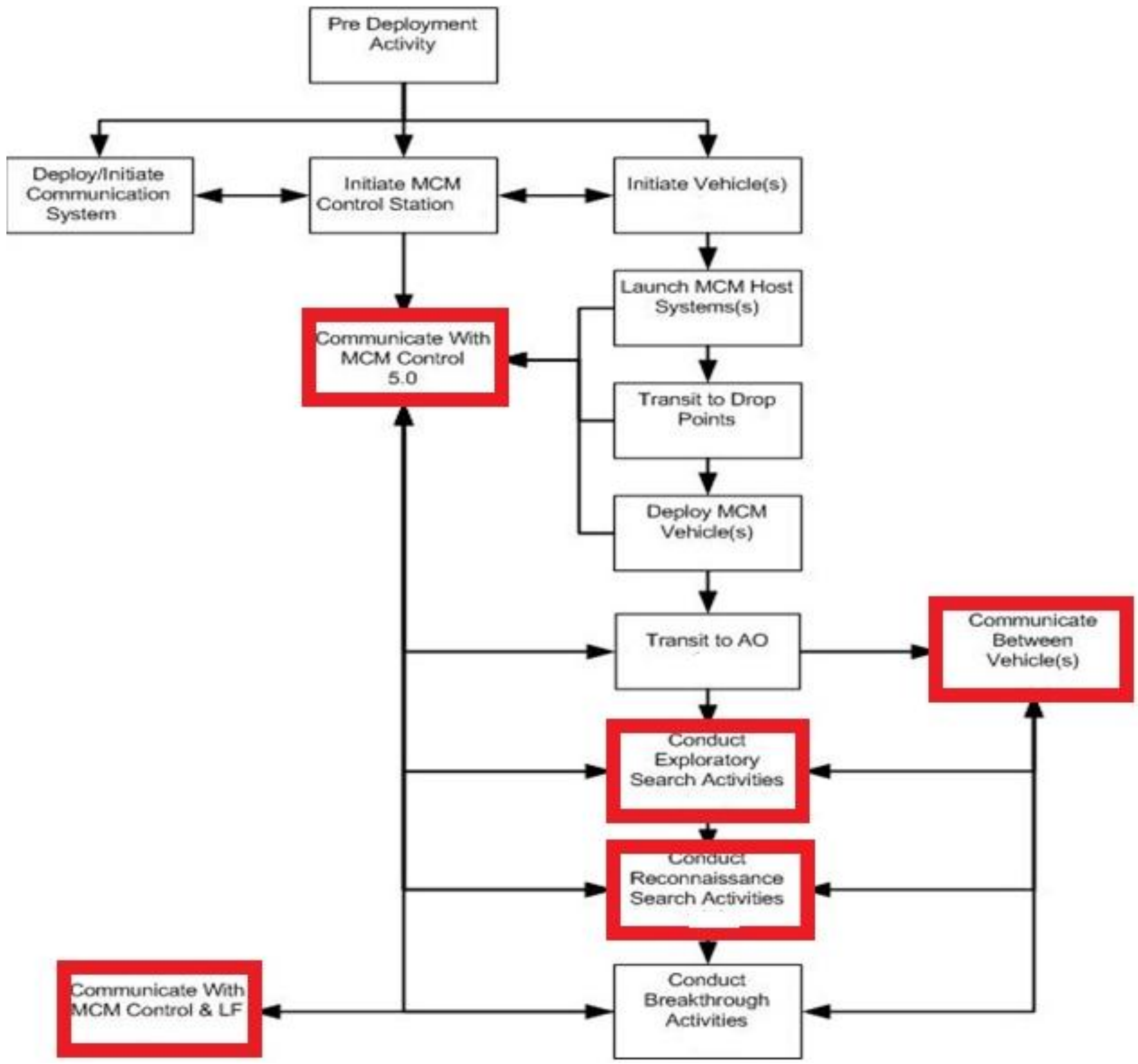

Figure 16. MCM System(s) Concept of Operation Activities

A concept for the activities of the deployment and operation of the MCM system. The activities that are bordered in red indicate those activities within the bounded system.

a. Pre Deployment Activity

During this activity the MCM system is prepared to be put into operation. The following is a list of some of the sub-activities:

1. The system(s) are unpacked and assembled.
2. Preventative Maintenance checks are done on systems.
3. System(s) are fueled or charged.

b. *Deploy/Initiate Communication System*

During this activity the communication system is either deployed or is initiated and established to facilitate communications OTH.

c. *Initiate MCM Control Station*

The MCM system will include a control station that is onboard a host platform. It will facilitate the command and control and collaboration for all the MCM operations and systems. The MCM control station will be used to develop the plan for the operation and will be used to create the mission parameters for the vehicles.

d. *Initiate Vehicle(s)*

Prior to this activity the vehicles are fueled or charged up. They are activated and loaded with mission parameters. Their navigation systems are synchronized with the host platform navigation systems.

e. *Communication with MCM Control*

During this activity all communication links with MCM control and host command and control is established. All external communication links are checked and monitored. This communication link will either be maintained or re-established as necessary during the entire search period. This communication will enable the controlling platform to control and direct the vehicles in the AO.

f. *Launch MCM Host System(s)*

During this activity the MCM system, or the transport platforms that carry the MCM system, are launched. The transport vehicle is delivers the MCM vehicle quickly and covertly to the deployment points. The AF will remain greater than 50 n.m. from the AO during the search period.

g. *Transit to Drop Points*

The MCM system will be carried by a transport vehicle to be deployed outside the area of operation. The transport vehicle will communicate with the MCM control station on departure and when it deploys MCM vehicles. The MCM system will be carried by a transport vehicle for deployment either 20 miles or 10 miles away from the area of operation depending on the mission requirements.

h. *Deploy MCM Vehicle(s)*

During this activity the MCM system is deployed from the transport vehicle. The transport vehicle will communicate with MCM control for status of the deployment. The

transport vehicle may or may not loiter at the deployment point during the period the MCM system transits to the area of operation.

i. Transit to Area of Operation (AO)

During this activity the MCM system shall transit from the deployment points to the AO. Upon successful deployment, the MCM system shall establish communication with MCM control and receive course and authorization to proceed.

j. Communicate between MCM Systems

Upon launch, the MCM system shall establish communication between any other MCM systems in the operation area. Depending upon the level of autonomy the communications will vary. This could be as simple as identification information or as complex as delivering tasking for the individual MCM system.

k. Conduct Exploratory Search Activities

Upon arrival at the AO the MCM vehicles will do the following:

1. Alert MCM control upon arrival
2. Receive last minute guidance and proceed with mission
3. Configure search patterns between vehicle(s)
4. Conduct quick search for the presence of mines
5. Refuel and recharge if necessary (Note: This refers to in AO refueling as the tasking platforms will be at a significant standoff distance.)
6. Report to MCM control the hydrographic conditions of the water routes
7. Report to MCM control the presences of mines and obstacle(s)

Upon completion of this activity, the MCM systems may or may not continue on to the next phase. Depending on the mission profile, they may loiter in the area or conduct refueling and recharging activities.

l. Conduct Reconnaissance Search Activities

During this activity, the MCM vehicle(s) receives further guidance of potential routes and reconfigures their search patterns. They will perform the following:

1. Detect, locate, classify and map every mine and obstacle along routes
2. Determines mine density and gaps along routes
3. Refuel and recharge
4. Communicate with between vehicle(s)
5. Communicate map back to MCM control

6. If necessary, communicates raw data back to MCM control for processing

Upon completion of this activity, the MCM vehicle(s) may or may not continue on to the next phase. They may loiter in the area or conduct refueling and recharging activities.

m. Conduct Breakthrough Activities

During this activity the MCM vehicles receive further guidance on routes, littoral penetration points and neutralization guidance of selected mines. The MCM vehicles will proceed to do the following:

1. Reacquire and neutralize suspected mines
2. Communicate status between vehicles
3. Communicate map and status back to MCM control

n. Communicate With MCM Control & LF

During this activity the MCM vehicles will communicate with the MCM host platform control station. The MCM host platform will then communicate with the LF which will update the status of their routes and activate markers for mines.

3. DRM Setup

The sea floor is described by both a category and by the clutter density. This will affect how well sensors are able to accurately detect the various objects on or buried in the sea floor.

Category A: Smooth sand with <10% case burial

Category B: Moderate sand with <10% case burial, or smooth sand with 20-75% case burial, or smooth-moderate mud/sand with 10-20%, or smooth rock with 0% case burial

Category C: rough sand with <10% case burial, or rough mud/sand with 10-20% case burial, or moderate mud with 20-75% case burial, or moderate-rough rock with 0% case burial

Category D: > 75 % mine case burial (Fuller, 2011)

Clutter Density 1: < 15 NOMBOs per nm^2

Clutter Density 2: 15 to 40 NOMBOs per nm^2

Clutter Density 3: >40 NOMBOs per nm^2 (Fuller, 2011)

The bottom type that was used in the minefield is B-2. This means that the sea floor is not completely smooth sand. It could be moderately rough sand, or mud. It can also be used to

describe the amount of burial a mine has. For example if a mine was in smooth sand buried up to 20-75%, it would be just as hard to see as the same mine buried less than 10% in moderately rough sand. The clutter density is based on non mine like bottom objects. This could be rocks, or other objects that are not mine like. These objects can hide a mine or at least slow down the search for the mines. In the minefields there will be between 15 and 40 NOMBOs for every nm^2.

a. Mission 1

An amphibious assault has been planned against an area where "Country Orange" has invaded and has built up a defense. The intent for the mission is to search an area in preparation for an amphibious assault which will be taking place in 3 days.

1. Since "Country Orange" is a hypothetical adversary, the data used to establish slope and currents is based on Guadalcanal in order to provide a starting point of reasonable values. The test area consisted of a grid 500 yards X 500 yards with sea floor depth starting at 10 ft and increasing at a 1˚ slope. A current of 2.5 knots was simulated. In this area of 500 yards by 500 yards, there were smaller areas where the depth increased or decreased. The changes in depth were no more than 5%. The average bottom composition was classified as B-2. In the test area there were 150 mines total consisting of 105 bottom mines with between 10% and 75% burial. There were also 45 moored mines. Alongside the mines there were 75 random non-mine objects such as man-made debris and environmental objects that could be detected as mine-like objects. The pattern of the mines was selected randomly and was used throughout all simulations of this mission to provide a common benchmark. The proposed systems were judged on percentage of mines detected and the time the search would take to complete. Successful completion was based on when the systems finished the search pattern and classifying and identifying the mine-like objects detected.
2. After the search is completed, the proposed systems used the neutralization plan that was developed to clear a path through the VSW zone.
3. The search time included any time required to replenish any consumables if required.

b. Mission 2

An amphibious assault has been planned against the same area as outlined in Mission 1, where "Country Orange" has invaded and has built up a defense. As with Mission 1, Guadalcanal was used as a template to determine reasonable values. The intent for the mission is to clear an area in preparations for an amphibious assault which will be occurring once the path is clear. Preliminary reconnaissance by other systems has indicated the chosen area is the best path to bring the assault force to shore. Although a path had been cleared, the opposition has been able to re-deploy mines into the area.

1. The test area consisted of a grid 500 yards X 500 yards with sea floor depth starting at 10 ft and increasing at a 1˚ slope. A current of 2.5 knots moving across the test area was simulated. In this area there were smaller areas where the depth increased or decreased. These changes in depth were no more than 5%. The average bottom composition was classified as B-2. In the test area there were 50 mines consisting of 40 bottom mines with between 10% and 75% burial. There were also 10 moored mines. Alongside the mines there were 75 random non-mine objects such as man-made debris and environmental objects that could be detected as mine-like objects. The mines were laid in 5 non-parallel lines covering the test area. The same pattern was used throughout all simulations of this mission to provide a common benchmark. The proposed systems were judged on percentage of mines detected and the time the search would take to complete. The systems were asked to classify, identify, and neutralize the mines.
2. The search time included any time required to replenish any consumables if required.

c. Replenishment

An amount of time was added if the system was unable to complete the mission without replenishment to simulate the act of in-mission range extension. Replenishment is for any fuel, energy source, or other materials that are required to allow the system to continue mine hunting and neutralization activities.

C. REQUIREMENTS

Following the development of the DRM, requirements were developed to successfully perform the outlined missions and bridge the capability gap.

1. Requirements for the MCM System

The following are the most important requirements the MCM System should be able to perform to in order to meet the capabilities and fill the gaps as identified earlier. The parenthesis following each requirement denote the objective ("O") value and the threshold ("T") value tied to the requirement. The following MCM system would include the MCM control stations which monitors and controls the MCM operation, the MCM vehicle and the MCM communication system.

1. (REQ 1.0): The MCM system that includes the vehicle and launch platform shall perform its MCM missions as clandestine operations. This requirement is further refined by:
    a. The MCM system shall have a 95% probability of not being detected with 90% confidence level by visual/IR sensors from the shore while performing search,

detect, classify, and mark in the VSW area during daylight hours and during times of high and low visibility.

b. The MCM system shall have a 80% (T), 95% (O) probability of not being detected by radar with 90% confidence level by shore based radar systems while performing search, detect, classify, and mark in the VSW area.
c. The MCM system magnetic signature shall have a 90% probability of not being detected with 90% confidence level while performing search, detect, classify, and mark in the VSW area.
d. The MCM system acoustic signature shall have a 90% probability of not being detected with 90% confidence level while performing search, detect, classify, and mark in the VSW area.

The rationale for these requirements came from the 2000 NRAC document entitled "Unmanned Vehicles (UV) in Mine Countermeasures" (Naval Research Advisory Committee, 2000). The document cites the need for UV to conduct clandestine MCM operations and indicates that in order for the UV to conduct MCM operations, it should have the capability of maintaining minimum radar, magnetic, and acoustic signatures (Bachkosky, et al., 2000). This cohort developed probability percentages based on sound engineering judgment. Current systems are concentrating on the ability to detect and classify mines and not focusing on performing covert operations. Therefore baseline probability numbers were not available from specifications or reports that this Cohort could use to develop these requirements. We recommend further research to create adequate baseline requirements based on specific mission needs.

2. (REQ 2.0): The MCM system shall have precise navigation which allows for a common tactical picture and provides for safe navigation, mine avoidance, and reacquisition if necessary for neutralization purposes.

This requirement is further refined by the following vehicle requirements:

a. The MCM system shall have onboard navigations systems that maintain accuracy of navigation to +/- 1 meter over a 48 hour operation period without receiving corrections from a ship or boat.
b. The MCM system shall maintain navigation accuracy of +/- 1 meter over a 48 hour period of operation in Sea State 4.
c. The MCM system navigation accuracy shall maintain stable and accurate platform navigation accounting for environment (i.e. current, crosswinds, and pressure). 0.01% of distance (O), 0.1% of distance (T)

d. The MCM system shall be to navigate either in autonomous or override for man-in-the-loop operation. MOTL/Auto (O), Auto (T)
e. The MCM system shall create navigation velocity information originating from navigational sensors (e.g. dead reckoning, INS, acoustic, Doppler velocity sonar/log (DVS/DVL), geophysical, ultra-short baseline/long baseline) geophysical, ultra-short baseline/long baseline) for live feedback for guidance. 0.01% velocity error (O), 0.1% velocity error (T)
f. The MCM system shall have obstacle avoidance abilities to evade objects in environment. all foreign objects within FOV (O), foreign objects $1ft^3$ within FOV (T)
g. The MCM system shall collect, store, process, and report navigation data information (e.g. bathymetric, position, attitude, heading, and bearing) through the network, provide all track info (100%) (O), provide vital track info (95%) (T)

The rationale for these requirement come from fact the system must be effective to locate, mark, and map mines and mine like objects. To complete the overall system requirements the system needs to be able to precisely navigate to the given AO and through the given area of interest. If the system can maintain an accurate location to within +/- 1 meter the obstacle or mine has a higher probability of being avoided or re-acquired for neutralization.

3. (REQ 3.0): The MCM system shall be capable of operating in autonomous modes. These autonomous modes could be Fully Autonomous, Semi-Autonomous, Tele-operation, and Remote Control as defined in the following requirements:

a. The MCM system shall be able to transition to and from AO, establish communication with other MCM assets, synchronize with other MCM assets, establish search patterns with other MCM assets, initiate search, detect, map, locate, identify, and classify UXO and Non-Mine, Mine-like Bottom Object (NOMBO) without human intervention. This mode of operation is called Fully Autonomous.
b. The MCM system shall be capable of performing search patterns and neutralization operations with permissions from human-robot interactions (HRI). This mode of operation is called Semi-Autonomous.
c. The MCM system, while operating in degraded mode, shall be capable of providing video and sensory feedback to a manual operator and accept waypoint guidance from HRI. This mode of operation is called Tele-operation.

d. The MCM system, while operating in a sensor fault mode, shall be capable of being continuously controlled via a radio link without providing video or sensory feedback to the MCM control ship. This mode of operation is called Remote Control.
e. The MCM system shall be able to accept tasking from a predetermined MCM platform.
f. The MCM system shall be able to create and transmit tasking to other MCM system.
g. The MCM system shall be able to receive and accept tasking from any other MCM system with authority to control.
h. MCM system shall be able to collaborate with other system without human operator interaction to organize, and synchronize search patterns and search techniques to detect, identify, and classify mines and non-mines.
i. The MCM system shall be capable of monitoring, reporting mission progress, provide mission level directions, coordinating missions, and tasking one or more MCM systems in a supervisor mode.
j. The MCM system shall adapt to systems failures or operational conditions that prevent it from continuing in its optimal mission profile and will react within the confines of its capabilities. This adaptation is called an adaptive mission profile.
k. The MCM system shall continue to perform the mission in a degraded mode unless commanded to do otherwise by the MCM command platform.

The rationale for this requirement is to remove the man from the mission operating environment and to reduce the man-footprint for operating the system.

4. (REQ 4.0): The MCM system shall have onboard processing capabilities to process targets, create reports, and create collaboration schemes for performing MCM operations. This requirement is further refined by:
    a. The MCM system shall create target reports that contain, target ID number, target location, time target was located, target type, and target fuse information.
    b. The MCM system shall create status reports that indicate the system unique ID and if the system is moving, searching, attacking, transiting, refueling, or performing a Built in Test (BIT).
    c. The MCM system status report failure indications shall indicate one or more of the following: All Subsystems Go, Navigation degraded, Navigation Fail, Sensor System Degraded with Sensor System Type Failed, Sensor System Failed, Onboard Processor Degraded, Onboard Power System Degraded, Propulsion or Steering Degraded, Propulsion or Steering Failed, Recording System Failed, and

Communication System Degraded. Indications will provide the further ability to investigate into the underlying problem in order to determine if the mission is still supportable given the failure.

The rationale for this requirement is to specify the types of reports the MCM system should receive or send to effectively enable the overall MCM system to perform the operation.

5. (REQ 5.0): The MCM communication system shall enable real time processing of MCM assets, mine contacts, support autonomous operations and support amphibious forces with situational awareness. This requirement is further refined by:
   a. The MCM system shall respond to and receive commands and reports from external systems to collaboratively conduct MCM missions.
   b. The MCM Control System shall communicate via net-centric overarching strategic and tactical networks.
   c. The MCM communication system shall create and broadcast status reports to support MCM and amphibious operations.

   The rationale for this requirement is that a real-time communications system must handle mission critical information and perform real-time computations. The system must enable the amphibious force to obtain information concerning the mission, enemy forces, neutral or non-combatants, friendly forces, terrain and weather. The rationale for MCM Control System to have net-centric strategic and tactical networks stems from MCT 5.1.1 to (Provide and Maintain Communications) to all send and receive data that includes verbal, electronic and written formats. Information can include plans, orders, intelligence, weather, friendly troop/unit status, and location reports (JP 1, 2-0 Series, 3-0, 3-56 Series, 6 Series, MCDP 6, MCWP 3-40.2, 3-40.3, NDP 6).

6. (REQ 6.0): In order for the MCM system to perform MCM missions, the system shall demonstrate endurance requirements to perform MCM missions for no less than 72 hours without requiring it to be recaptured or deactivated to perform maintenance or preventative maintenance. This requirement is further refined by:
   a. The sustained area coverage rate for the MCM system shall not be less than 0.083 n.m.^{2}/hr (T) and 0.125 n.m.^{2}/hr (O) (assuming an area of 500 yards long by 26 nautical miles wide).
   b. The MCM system shall be able to sustain 30 knot speed without need for refueling in sea state 4 while transitioning from the distant retirement area to AO.
   c. The MCM system shall have an endurance of 48 hours without requiring refueling while conducting normal MCM operations.

The rationale for this requirement is that the MCM system must be able to cover a large area to ensure it is able to map the best approach lane for the amphibious landing. The MCM system must be able to arrive at the area of interest in a timely fashion. The time needed by the MCM system to arrive at a given location is directly related to the overall mission time. For reference, the current endurance requirement for a lightweight vehicle is 20 hours. Paragraph c above defines the total search is between 17.4 and 34.8 miles. Therefore, it was deemed reasonable that the vehicle should cover the average distance of 26 n.m..

7. (REQ 7.0): The MCM system shall be designed to operate in the air (for navigation equipment to be working prior to an aerial drop), surface, and subsurface environment in support of worldwide amphibious operations. It is envisioned that a MCM system can be developed that can operate from air, surface or subsurface platform. Even though the system may not be performing MCM functions, it may be required to be powered so that it can be programmed with last minute launch instructions or navigation coordinates or be required to perform BIT. This requirement is further refined by:
    a. The MCM system shall be able to be launched and operate in sea state 3 (T), and sea state of 4 (O).
    b. The MCM system shall be capable of operating in water temperatures from 28°F (0°C) to 90°F (32°C).
    c. The MCM system shall be capable of operating in a temperature range of -45^{o}F (-49^{o}C) to 176^{o}F (80^{o}C) (air temperature; protected from direct sunlight). Rationale for requirement: MIL-HDBK-310 states a high of 58^{o}C (136^{o}F) was recorded in El Azziza Libya in Sept 1922. Additionally the lowest temperature recorded was -68^{o}C (-90^{o}F) in Verkhoyansk Russia 7 Feb 1892. (Global Climate Data for Developing Military Products, 1987). Operation of electronic equipment often generates additional heat that can further degrade performance in such an area without specialized cooling, making such extreme temperature requirements necessary for deployment in all types of areas.
    d. The MCM system shall withstand a thermal shock associated with exposure to a 18°F per minute rate of temperature change, to temperature extremes of -20°F (-28.9°C) and 109°F (43°C) (air).
    e. The MCM system shall be capable of operating (i.e., transit and maneuver, not search-classify-map) at water depths up to (threshold) 300, and (objective) 900 Feet of Sea Water (FSW). Rationale for requirement: The MK18 is specified to operate at 300 FSW (Fournier, 2011) and the Hydrographic Multibeam Replacement Sonar is specified to operate down to 400 meters 1312 ft. Even though it is not envisioned that the system will not search for mines at 900 FSW;

it may be required to lie dormant in 900 feet of water. It is envisioned that a system could be covertly seeded in the AI and not be activate for use until needed. The system would be required to operate to move after a time of lying dormant.

f. The MCM system shall be capable of operating (i.e., transit and maneuver, not search-classify-map) at the surface of the water.
g. The MCM system shall be capable of operating in a current less than or equal to (threshold) 5 kts, (objective) 10kts flowing in any direction.
h. The MCM system and all other components intended for in-water operations shall be capable of operating in water having a salinity level up to (threshold) 45 parts per thousand (ppt).
i. The MCM system shall be capable of operating within turbidity conditions up to and including (threshold) 66 mg/l (~ 8 Nephlometric Turbidity Units (NTU)) of suspended particulate matter, as measured by a Formazin calibrated optical backscatter meter.
j. The MCM system shall be capable of being recovered.

The rationale for this requirement is that the MCM system must be able to operate over wide temperature, pressure and other environmental extremes to meet the Navy's worldwide service.

8. (REQ 8.0): The MCM System shall be capable of rapid deployment from a minimum of 50 nautical miles from AO; where deployment is defined as the time needed to transition from a storage state on a host platform to actual launch and operation in the water.

9. (REQ 9.0): The MCM system shall be capable of detecting and classifying mines. This requirement is further refined by:
   a. The MCM system shall be able detect, classify, and map both bottom and moored mines in a VSW area in a time frame of less than or not greater than threshold 48 hours, objective 24 hours.
   b. The MCM System shall trigger an alert for a suspect mine-like object
   c. The MCM systems shall be able to transmit mine location, mine identification information, and urgent reports to other MCM systems and MCM control.

10. (REQ 10.0): The MCM system shall be able to execute collaborative search patterns from multiple pre-mission loaded search patterns for the AO. The MCM system shall be able to adjust search patterns while underway based on input or tasking from other MCM systems and platforms.

11. (REQ 11.0): The MCM system shall be capable of neutralizing mines.
    a. Upon receiving a command to neutralize a mine, the MCM system shall reacquire the mine within 10 minutes (T), 5 minutes (O) for neutralization.
    b. The MCM system shall be capable of neutralizing the effects of mines in clearing (threshold) 8, or (objective) 16 Littoral Penetration Points and boat lanes in the VSW area within 48 hours (Neller, 2005).

    The rationale for time requirements is that systems will first perform a reconnaissance and map the mines along routes and pass this information back to the MCM control. A mine is considered effectively neutralized if its location is known and it can be avoided. If a mine cannot be avoided then other options must be considered to destroy the mine or neutralize its ability to detect an intended target or its ability to detonate. Once the control determines what lanes to clear it will issue orders to clear certain mines. Since the vehicle should know where the mines are, it is envisioned that it should not take more that 10 minutes to reacquire the mine for neutralization. The rationale for clearance requirement of 48 hours is the following: The overall mission to clear all the lanes for the amphibious force is 72 hours. However, clearing the VSW area is just a portion of the overall area that must be cleared. Therefore assigning 72 hours to clearing a path in the VSW area would not account for the time to deploy the vehicles and clear the area outside the VSW area. Therefore, since the VSW area is the hardest area to detect and locate mines; 2/3 of the total 72 hour mission time was deemed necessary to clear paths in the VSW area. This calculates out to 48 hours.

12. (REQ 12.0): The MCM system shall incorporate multiple sensor(s) to enable the MCM system to detect, identify, locate, and classify observable features of UXO in all regions of water to include the VSW region. This requirement is further refined by:
    a. The MCM system sensors shall be able to create a full 360 degree view of the target to enable identification.
    b. The MCM system sensors shall be to detect the presence of explosives through the use of chemical sensors.
    c. The MCM system sensors shall incorporate a 3-D level as objective, 2-D as threshold sonar system with high resolution.
    d. The MCM system shall demonstrate the ability to place its sensor to observe the target from any angle available.
    e. The MCM system shall contain a biomimetic sonar for detection of buried bottom mines.
    f. The MCM system vehicle shall incorporate combined acoustic and high resolution visual sensor systems to identify UXO in turbid waters.

g. The MCM system shall incorporate a magnetic gradiometer that can be extended away the MCM vehicle body to mitigate the noise effects of the MCM vehicle and to enable the MCM system to detect shallow water bottom buried mines (Yaun, Hock, Xiao, Soon, & Teck, 2010; Hagen, 2010).
h. If GPS is used for navigation of the MCM system during ingress, egress, and/or search-classify-map (S-C-M), it shall use military P-code capable receivers.

2. Other Important Requirements for the MCM System

The following requirements are important for the MCM system to meet; however, these requirements are not as important to meet as the top requirements. Only partially meeting these requirements will still enable a successful system.

1. (REQ 13.0): The MCM system shall be designed to operate in the electromagnetic (EM) Naval Air, Surface, and Subsurface environments per MIL-STD-461 without failure or degradation in performance

   The rationale for this requirement is that the MCM system must be able to operate over wide environmental extremes to include the electromagnetic environment. It is important the MCM system operate without degradation in the electromagnetic environment. However there are tests that the system could fail and still be considered capable to perform its mission.

2. (REQ 14.0): In order for the MCM system to perform MCM missions, the MCM system shall be reliable and available. This requirement is further refined by:
   a. The MCM system shall have an operational availability of not less than 95% (O), 85% (T). This A_o is for the overall system availability including the MCM command & control system, MCM vehicles, MCM communication nodes, and MCM deploy and recovery system.
   b. The MCM system shall be designed for maintainability with repairable subsystems having less than 1 hour mean time to repair (MTTR) on single point failures and 3 hours for non-critical failures. This MTTR is for the overall system including the MCM command & control system, MCM vehicles, MCM communication nodes, and MCM deploy and recovery system.
   c. The MCM system shall have a mean time between failure (MTBF) of not less than 100 hours (T), 300 hours (O) with 95% confidence.

3. (REQ 15.0): The MCM system shall be able to be launched by a subsurface, surface or air platform. This requirement is further refined by:

   a. The MCM system shall be recovered by a subsurface or surface platform within 15 minutes of closure with an MCM vehicle and launch platform.
   b. The preparation of the MCM system for launch shall not be greater than 15minutes.
   c. The actual launch sequence of the MCM system shall not take longer than 10 minutes after preparation for launch and the launch command is given.

   The rationale for this requirement is that current launch and recovery take up a significant portion of the allotted detect-to-engage sequence time (Operators, 2011). Designing for rapid launch and recovery will provide more time to complete the MCM mission in the operations area, rather than using this time onboard the command platform.

4. (REQ 16.0): The MCM system shall minimize the system weight and footprint by implementing a modular design. This requirement is further refined by:
   a. The MCM vehicle/payload weight shall not be more than 753 pounds (Honeywell, 1982).
   b. The MCM system shall be capable of receiving in-situ range and operation extension upon depleting onboard energy reserves.

   The rationale for this requirement is that storage room on MCM ships is being reduced. The physical size of the vehicle should not be larger than MK50 torpedoes to ensure they can be deployed from aircraft. The size of the control stations and storage units need to be sized to go on any ship. The design should be modular to allow ease of upgrading the MCM system with future technology and/or to change the configuration of the platform based on mission requirements.

5. (REQ 17.0): The MCM system shall be equipped with an approved Weapons Safety Explosive Safety Review Board (WSESRB) fire control solution during operation and implement safety interlocks and keep-out zones for servicing to minimize human hazards and risks.

6. (REQ 18.0): The system shall implement modular open systems software architecture for ease of portability, upgrading, and troubleshooting.

D. SYSTEM METRICS

System metrics provide an avenue to compare alternative system architectures by identifying and defining system effectiveness measures that reflect overall stakeholder expectations and satisfaction. Metrics drive the detailed design of the system to meet specific metric threshold values as well as allowing verification and validation of the system requirements and functions, providing traceability of metrics to stakeholder requirements and operational functions.

1. System Metrics Selection Process

Since a great deal of the determination of system metrics relied on understanding the needs of the system, stakeholder needs were analyzed first. Some of the stakeholder needs include reducing the DTE, addressing OTH operations, and reducing human error due to human fatigue. These, as well as other stakeholder needs, were analyzed to develop a set of metrics that would help in the analysis of performance of system design alternatives. System requirements and functions were also analyzed to help determine the metrics. Table 6 displays the result of these three analyses to determine the high level system parameters that would drive the creation of system metrics.

Table 6. High Level System Parameters that drive System Metrics

Result of analysis of stakeholder needs, requirements, and functions to determine high level system parameters from each category that would drive the creation of overarching system metrics to analyze the performance of the developed system at a high level.

High Level Stakeholder Needs	High Level Requirements	High Level System Functions
1. Area that can be covered with implemented system 2. Number of persons in the minefield at any given time 3. Area coverage rate 4. False detection rate 5. Implementation of a real-time data processing capability between system components 6. Number of operators 7. Transit speed	REQ 1.0: Clandestine Operations REQ 2.0: Navigation Precision REQ 3.0: Autonomous Operational Modes REQ 4.0: Processing Capabilities REQ 4.0: MCM Communication REQ 6.0: Endurance REQ 7.0: Operational Environment REQ 8.0: Deployment Distance REQ 9.0: Detection and Classification REQ 10.0: Collaborative Search Patterns REQ 11.0: Mine Neutralization REQ 12.0: Multiple Sensors REQ 13.0: Electromagnetic Environment REQ 14.0: Reliable and Available REQ 15.0: Launch Platform REQ 16.0: Minimize Weight, Footprint REQ 17.0: Weapon Safety REQ 18.0: Software Architecture	1. (FD.1) Detect 2. (FC.2) Classify 3. (FI.3) Identify 4. (FE.4) Engage 5. (FT.5) Transit 6. (FCO.6) Communicate 7. (FS.7) Search 8. (FDE.8) Deploy 9. (FRM.9)Receive Maintenance 10.(FFP.10)Perform Planning 11.(FR.11) Recover

2. System Metrics Selection

Table 7 depicts the final MCM system metrics along with units of measure that were derived from an analysis of Table 6. The comparison of stakeholder need, requirements and functions showed that all three areas address the concern related to clearing and searching the minefield area in an effective amount of time. This translated to the first identified metric of ACR.

Along with correctly identifying the mines, the comparison analysis also identified the need to reduce the amount of mine targets that are missed during search operations. Misinterpreting or not properly identifying a mine could cause catastrophic results. As a result, the concern for measuring the percentage of mines a system would miss during a search was translated to the Undetected Mines metric.

Lastly, the reduction in manning, surface presence of support craft and successfully conducting all mission phases with a low profile was identified as a common concern. This was the determination for identifying Stealthiness as a comparison metric as shown in Table 7.

Table 7. MCM System Metrics

The data presented is the culmination of the iterative process of comparing stakeholder needs, current capability gaps, threat analysis, functional analysis, and system requirements. These metrics were used to compare alternative system architectures.

System Measures of Effectiveness	Unit of Measure
AREA COVERAGE RATE	Nautical Miles^2/Hour (nmi²/hr)
UNDETECTED MINES	% of Total Mines Undetected
STEALTH	Probability of Detection by Enemy (%)

3. System Metrics Definitions

a. Area Coverage Rate

The area coverage rate is defined as how fast the system can complete the detect-to-engage sequence in the clearance of an area for safe operations to occur. The unit of measure for this metric is the nautical miles (squared) covered per each search hour. For the purposes of this report, the engagement of the mine can be considered any means that renders the mine ineffective against an amphibious landing force. For example, in some cases this may mean marking and mapping the mines, while in other cases the engagement may entail the complete destruction of a mine with explosives, chemicals, and Electronic Warfare (EW) technologies.

b. Undetected Mines

The undetected mine is a metric chosen to represent targets missed by the system. Targets missed by systems cause a significant increased risk to amphibious landing teams, increasing the risk of loss of a human life.

c. Stealth

Stealth measures the system's ability to carry out operations in a covert manner. The system must be designed with mechanisms to isolate and avoid mechanical noises that could reveal location to underwater passive sonar arrays or submerged acoustic system like submarines. Stealth capabilities must allow the system to be undetected from autonomous acoustic sensor systems used in battlefield awareness and other wide range surveillances such as visual and radar scans. Covert operation will result in relaxing the need to provide suppression fire in the obscuration activity of the MCM breakthrough phase. If MCM can be conducted without detection, the opposing force will not react hostilely and expose forces to unnecessary risk. Stealth will be measured as a function of the probability of detection by enemy forces.

E. FUNCTIONAL ARCHITECTURE

1. Functional Decomposition

In order to accommodate the overall need to reduce the time it takes to clear a minefield in support of an amphibious assault, high level functions from current doctrine need to be addressed. These are Detect, Classify, Identify, and Engage. From the capabilities analysis and stakeholder analysis, it was discovered that current systems take a long time to transition from the Identify function to the Engage function. Many times this transition is delayed due to the lack of real-time communications or the lack of ability for the system to Classify and Identify the mines autonomously. This in turn requires the system to be recovered and the data to be downloaded and analyzed before the Engage function can be performed. During the Engage function the current mission sequence requires the system to re-acquire the contact before it can be neutralized causing further delay in completing the DTE sequence.

The goal of the functional analysis was to take capability gaps in conjunction with the current doctrine and requirements analysis to develop functions that further develop system details and tasking. Since one of the major capability gaps defined was the lack of real-time communications, the Communicate function was created to manage the interfaces with the environment external to the system as well as connect the MCM vehicle to the host platform. The remaining high level functions derived were mapped to at least one top level requirement and describe the tasks to be performed in detecting a mine within the VSW zone. These functions include the Deploy, Recover, Perform Planning, and Receive Maintenance functions. Additional task development outside of the VSW zone includes mission planning, the platform launch and transit from outside the operational area of interest, and the platform's recovery. Varying degrees of sub-functions were added to the high level functions to provide needed expansion where multiple tasks were involved. Vitech Corporation's CORE software was used to model the system's solution-neutral architecture by providing a medium to map out the functions and sub-functions while enabling the linking of requirements to pertinent functions. At the conclusion of the functional decomposition, all developed requirements were linked to their implementation function and a sound solution-neutral architectural model existed in CORE that fed into the development of alternative architectures and the DRM.

2. Functions

Figure 17 shows the general functional flow of the DTE sequence to complete a mission in the VSW zone by a single detection platform. The following section contains a brief overview of the functions created and modeled in CORE. Linking of the functions' inputs, outputs, and triggers was performed in CORE and is not listed in subsequent descriptions in order to provide an overview of the functional architecture.

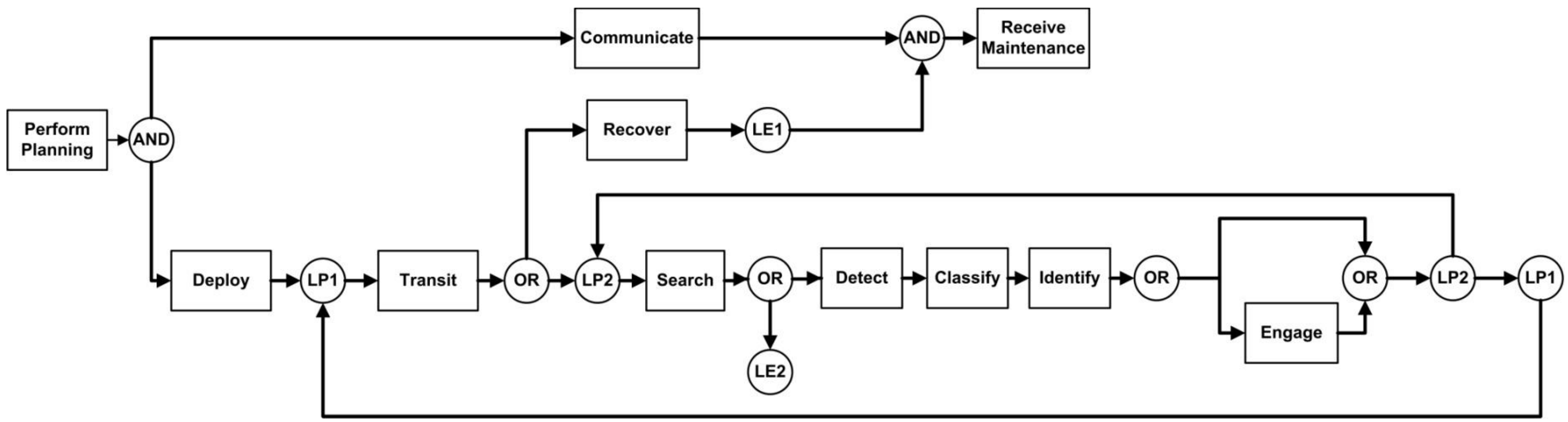

Figure 17. Functional Flow Block Diagram of MCM Detect to Engage Sequence

Functional Flow Block Diagram (FFBD) of functions performed by MCM system during a mission conducted in the VSW zone. Walking through the FFBD, the mission starts with the Perform Planning Function. Once Perform Planning completes, both the Communicate function and Deploy functions start. The Communicate function performs the communications from the MCM system to external systems and is active throughout the duration of the mission, until the MCM system is recovered. After the Deploy function, the first loop, LP1, is entered and the Transit function starts, where the MCM system transits into or out of an operational area depending on direction given by the host platform. With the completion of the transit function, either the Recover function is called to recover the MCM system (if the system has transited to a recovery point), or a second loop is entered to search for mines in the operational area (if the MCM system has transited into a search area). Entering the second loop, LP2, begins the Search-Detect-Classify-Identify sequence. The Search function effectively "mows the lawn" in the operational area looking for mine-like objects. If a mine-like object is detected, the Search function ends and the Detect-Classify-Identify sequence starts for the mine-like object. Once the Identify function has completed, a decision is made whether to engage or not engage the detected mine. Once this decision is made, either the Engage function is called, or it is bypassed. After the Engage function completes or is bypassed, the second loop, LP2, restarts at the Search function, searching the operational area again for a new mine-like contact. LP2 is exited if the MCM system reaches the end of the operational area, or is directed to stop searching during the Search function. This exit of the second loop is noted on the FFBD as "LE2", the loop exit. When LP2 ends, the first loop, LP1, is restarted and the transit function is called again to move the MCM system to a new operational area to further prosecute mines or to a recovery point to recover the MCM system. Once the Communicate and Recovery functions have completed, the Receive Maintenance function is performed at the end of the mission.

a. *Perform Planning*

Figure 18 depicts the functional hierarchy of the Perform Planning function. The Perform Planning function describes events where either a tasking authority or the MCM platform itself is planning or accepting a search. Since all system actions depend on a predetermined set of parameters, planning the search and the DTE actions need to be handled onboard, with some input from outside systems. The Perform Planning function includes four sub-functions:

1. FPP.10.1 Create tasking for MCM assets
2. FPP.10.2 Accept search plans
3. FPP.10.3 Accept tasking from MCM assets
4. FPP.10.4 Create message about contacts (*anticipated mine locations in AO*)

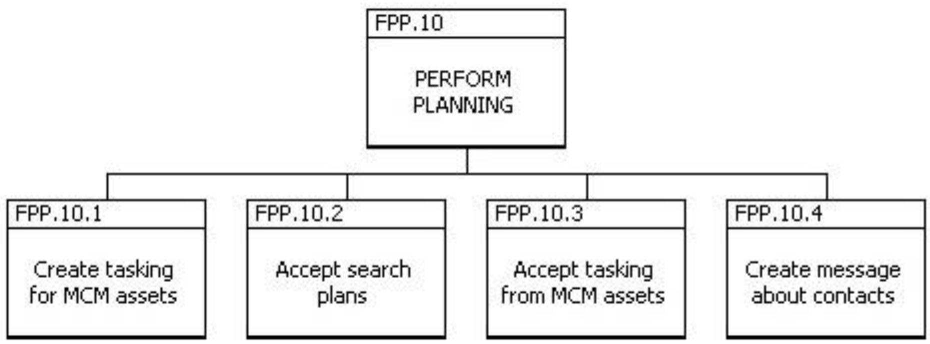

Figure 18. Perform Planning Function Hierarchy

Functional decomposition of the Perform Planning function. The Perform Planning function describes events where either a tasking authority or the MCM platform itself is planning or accepting a search.

b. Deploy

Figure 20 depicts the functional hierarchy of the deploy function. Since the amphibious task force will be stationed at a standoff distance from the operational area, there is a need to have flexibility in the deployment of the system. Depending on the required level of covertness for the individual mission, it would be possible that the system would need to be launched by either air, surface or sub-surface vehicles. The top level deploy function describes events at the start of the DTE sequence with the platform being deployed into the field. The deploy function includes three sub-functions:

1. FDE.8.1 Deploy from sub-surface craft
2. FDE.8.2 Deploy from surface craft
3. FDE.8.3 Deploy from aircraft

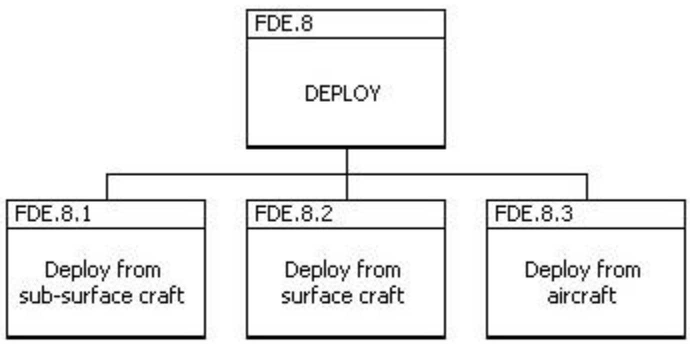

Figure 19. Deploy Functional Hierarchy

Functional decomposition of the Deploy function. The Deploy function describes events at the start of the DTE sequence with the platform being deployed into the field.

c. Recover

Figure 20 depicts the functional hierarchy of the recover function. Since the amphibious task force will be stationed at a standoff distance from the operational area, there is a need to recover the system after it has completed its mission. The top level recover function describes events at the end of the DTE sequence with the platform being recovered from the field at a recovery point. An emergency recover function was included as a sub-function to account for the recovery of a system with an unrecoverable failure during the mission. The recover function includes two sub-functions:

1. FR.11.1 Recover from surface craft
2. FR.11.2 Emergency recover

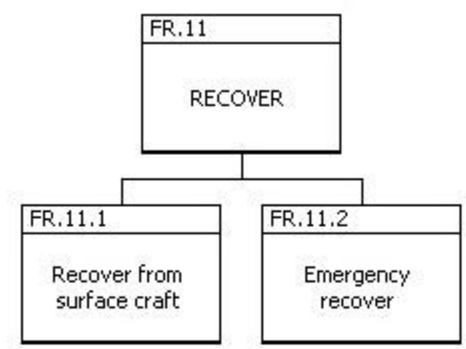

Figure 20. Recover Function Hierarchy

Functional decomposition of the Recover function. The Recover function describes events at the end of the DTE sequence with the platform being recovered from the field. An emergency recover function was included as a sub-function to account for the recovery of a system with an unrecoverable failure during the mission.

d. Transit

Figure 21 depicts the functional hierarchy of the transit function. The transit function describes events immediately before and after the search function where the MCM platform is transiting to and away from the operational area of interest. Since the amphibious task force will be stationed at a standoff distance from the AO, the system will need to travel from the deployment location to the AO. In order to reduce the probability of detection of the system by the adversary it will be not be practical to deploy the system in the AO. This being the case, the system will need to be able to travel to the area in a covert method. The transit function includes eight sub-functions:

1. FT.5.1 Determine deployment coordinates
2. FT.5.2 Determine path to operational area
3. FT.5.3 Engage navigational sensors
4. FT.5.4 Engage transiting system
5. FT.5.5 Transit and monitor for obstacles
    a. FT.5.5.1 Continue transiting clear path
    b. FT.5.5.2 Modify path to avoid obstacle
6. FT.5.6 Acknowledge entering search areas
7. FT.5.7 Determine direction and distance to recovery point
8. FT.5.8 Create message indicating arrival at recovery point

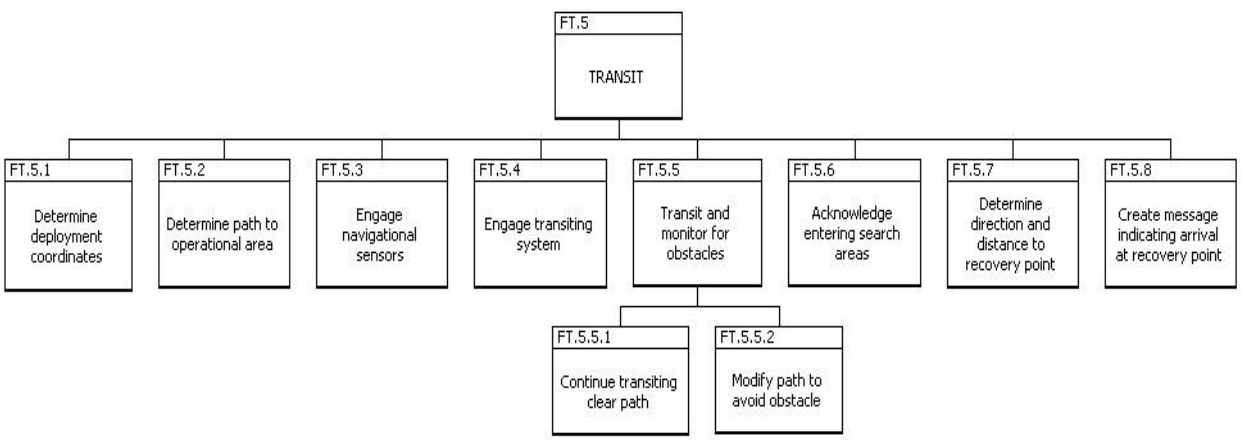

Figure 21. Transit Function Hierarchy

Functional decomposition of the Transit function. The Transit function describes events immediately before and after the search function where the MCM platform is transiting to and away from the operational area of interest.

e. Search

Figure 22 depicts the functional hierarchy of the search function. The top level search function describes events when the platform has reached the operational area of interest and starts to perform the search functions to detect contacts. As part of the overall need to find mine-like objects that would prevent an amphibious assault from being performed, the search function provides the ability for the system to detect the mines. Sub-functions include the initialization and deactivation of the search sensors and the modification of the search pattern in response to detected contacts and other events in the mission. The search function includes six sub-functions:

1. FS.7.1 Enter operational area
2. FS.7.2 Activate search sensors
3. FS.7.3 Follow search commands
    a. FS.7.3.1 Follow programmed search pattern
    b. FS.7.3.2 Determine if search pattern should be modified
    c. FS.7.3.3 Change search program
4. FS.7.4 Record platform location
5. FS.7.5 Create mission complete message
6. FS.7.6 Deactivate search sensors

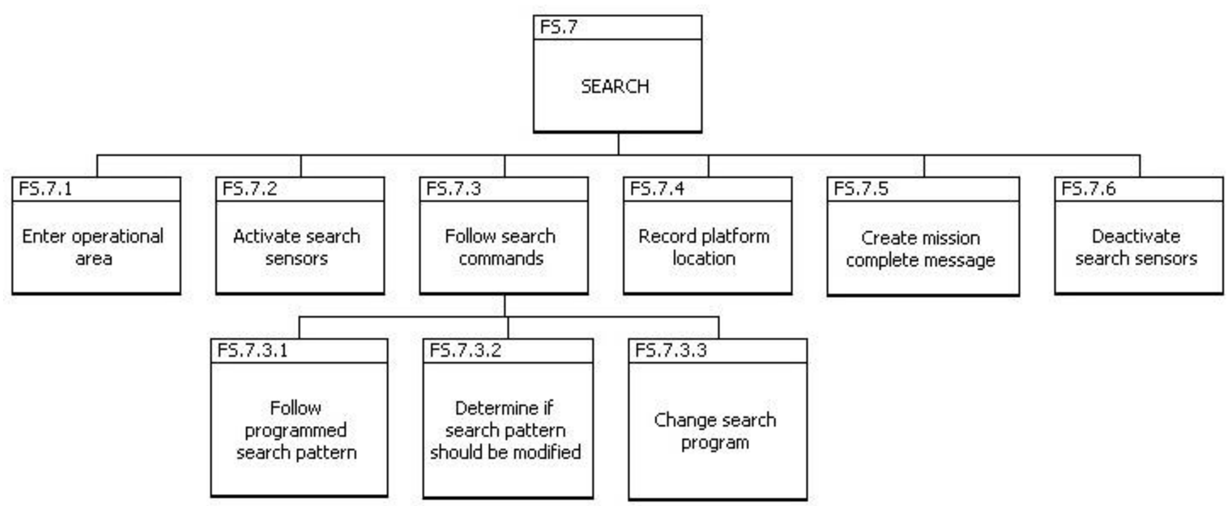

Figure 22. Search Function Hierarchy

Functional decomposition of the Search function. The Search function describes events when the platform has reached the operational area of interest and starts to perform the search functions to detect contacts.

f. Detect

Figure 23 depicts the functional hierarchy of the detect function. The high level detect function describes the events of receiving contact information from system sensors, recording both location and environmental information from the sensors, and creating a message to transmit indicating the detection of a contact in the path of the detection platform. The need for this function comes from the overarching problem of locating mine-like objects. This function fulfills many requirements involving first the detection of a contact, and then recording of the contact's location. The detect function also fulfills requirements to create a report for mission analysis personnel. If a mine is unable to be detected, the rest of the functions will not be able to meet the need of the end user. The detect function includes four sub-functions:

1. FD.1.1 Receive information from sensors indicating contact in the area
2. FD.1.2 Record location of contact
3. FD.1.3 Record environmental information from sensors
4. FD.1.4 Create message about a detection in the area and its location

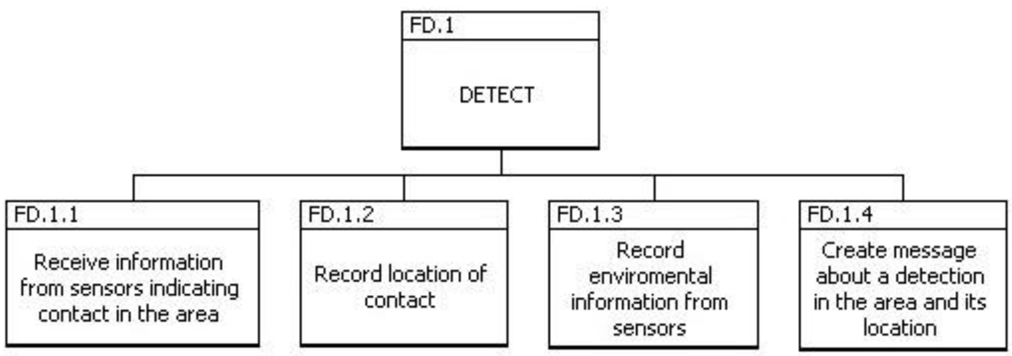

Figure 23. Detect Function Hierarchy

Functional decomposition of the Detect function. The Detect function describes the events of receiving contact information from system sensors, recording both location and environmental information from the sensors, and creating a message to transmit indicating the detection of a contact in the path of the detection platform.

g. Classify

Figure 24 depicts the functional hierarchy of the classify function. The high level classify function describes events directly after a contact is detected and is determined to be either a mine-like or non-mine-like object. If an object is classified as non-mine-like, then the system can ignore and continue with the search. However, if the contact is determined to be mine-like then either the system or the operator must take further steps to determine the level the threat it poses. Any mine-like object will prevent the amphibious assault from occurring unless steps are taken to neutralize the object. The classify function includes three sub-functions:

1. FC.2.1 Process sensor input
2. FC.2.2 Determine if contact is mine-like or non-mine-like
3. FC.2.3 Create message about contact classification

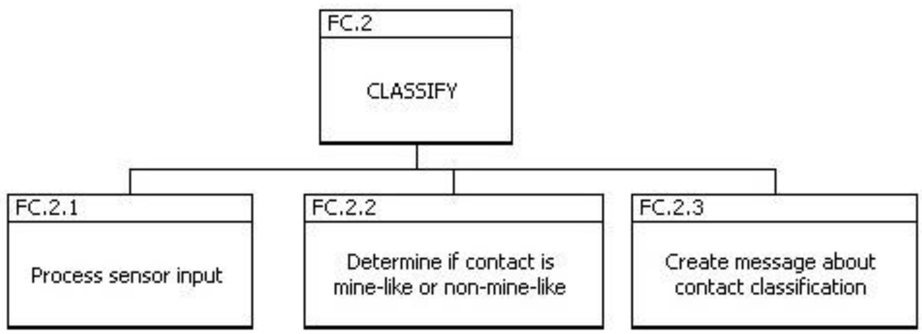

Figure 24. Classify Function Hierarchy

Functional decomposition of the Classify function. The Classify function describes events directly after a contact is detected and is determined to be either a mine-like or non-mine-like object.

h. Identify

Figure 25 depicts the functional hierarchy of the identify function. The top level identify function describes events triggered by the classify function determining a mine-like contact has been found. The identify function proceeds to further identify a mine-like contact as either bottom, moored, or drifting mine. If the contact is non-mine-like, the system will determine if the contact could cause a threat to the detection platform and must be avoided. This could come in the form of a large rock, or other obstacle in the path of the system. The identify function creates a message to be transmitted from the system indicating further information about the mine-like contact. The identify function includes five sub-functions:

1. FI.3.1 Determine if mine-like contact is a bottom mine
2. FI.3.2 Determine if mine-like contact is moored mine
3. FI.3.3 Determine if mine-like contact is drifting mine
4. FI.3.4 Determine if mine-like contact should be avoided
5. FI.3.5 Create message about mine identification

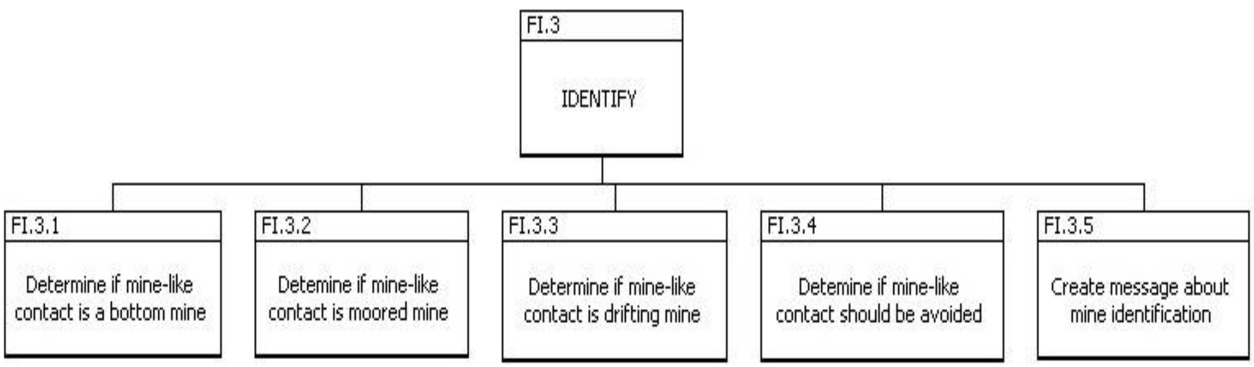

Figure 25. Identify Function Hierarchy

Functional decomposition of the Identify function. The Identify function describes events triggered by the classify function determining a mine-like contact has been found. The Identify function proceeds to further identify a mine-like contact as either bottom, moored, or drifting mine.

i. Engage

The top level engage function describes events triggered by a mine-like contact being detected and determines the need to engage. The engage function processes inputs of information on the mine-like contact of interest from previous steps in the DTE sequence. There are several ways to engage a mine. The one method is to determine the mine's exact location, mark it and avoid the mine's surrounding area when transiting the area. Another way is to neutralize the mine real time as it is found and identified. However, some situations require that

the mine is identified and located during an initial search (reconnaissance mission) with neutralization occurring later (re-acquire and neutralize mission). Locating the mine a second time should not take as long since the location is already known. The neutralization sub-function, if triggered performs the functions related to neutralizing the mine-like contact. The engage function includes four sub-functions with one sub-function containing three lower-level functions:

1. FE.4.1 Create Neutralization Plan
    a. FE.4.1.1 Determine necessity and method for neutralization
    b. FE.4.1.2 Create message requesting approval of neutralization plan
    c. FE.4.1.3 Neutralization plan approved/modified by tasking authority
2. FE.4.2 Reacquire (Note: Reacquire takes into account if the Engage function is not called directly after the Identify function, the mine will need to be relocated to effectively neutralize it.)
3. FE.4.3 Neutralize contact (disable contact)
4. FE.4.4 Create message about engagement results

Figure 26 depicts the functional hierarchy of the engage function.

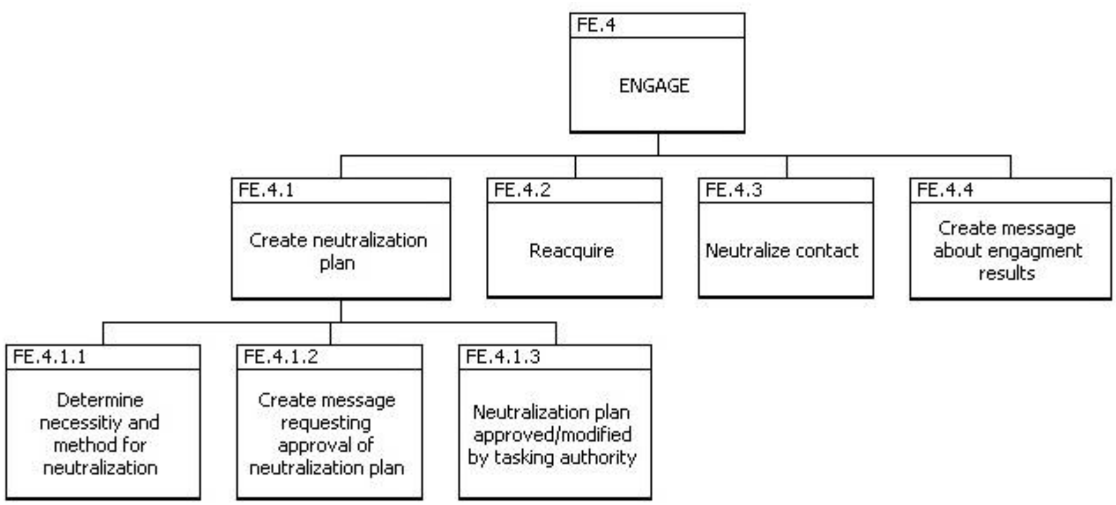

Figure 26. Engage Function Hierarchy

Functional decomposition of the Engage function. The Engage function describes events triggered by a mine-like contact being detected and determines the need to engage. The Engage function processes inputs of information on the mine-like contact of interest from previous steps in the DTE sequence.

j. *Communicate*

Figure 27 depicts the functional hierarchy of the communicate function. The communicate function describes the link between all the MCM platforms performing the mission and exists throughout the whole mission from start to finish. Communicate is how the platform sends and receives information by any means while deployed. Since one of the short comings of current systems, though becoming more prevalent in emerging systems, is that real-time communications are lacking, the communicate function is critical in providing information to other MCM systems and to the amphibious task force. The determine status function relays functional status to the tasking authority and provides alerts if the system becomes degraded to a point where the mission is impacted. The communicate function includes four sub-functions:

1. FCO.6.1 Receive communications
    a. FCO.6.1.1 Receive hard connect communications
    b. FCO.6.1.2 Receive wireless communications
2. FCO.6.2 Transmit communications
    a. FCO.6.2.1 Transmit hard connect communications
    b. FCO.6.2.2 Transmit wireless communications
3. FCO.6.3 Determine Status (in-mission status)
    a. FCO.6.3.1 Perform BIT (Built-In-Test)
    b. FCO.6.3.2 Create message about operational status, including errors
    c. FCO.6.3.3 Determine time, locations, direction, and speed
4. FCO.6.4 Store information

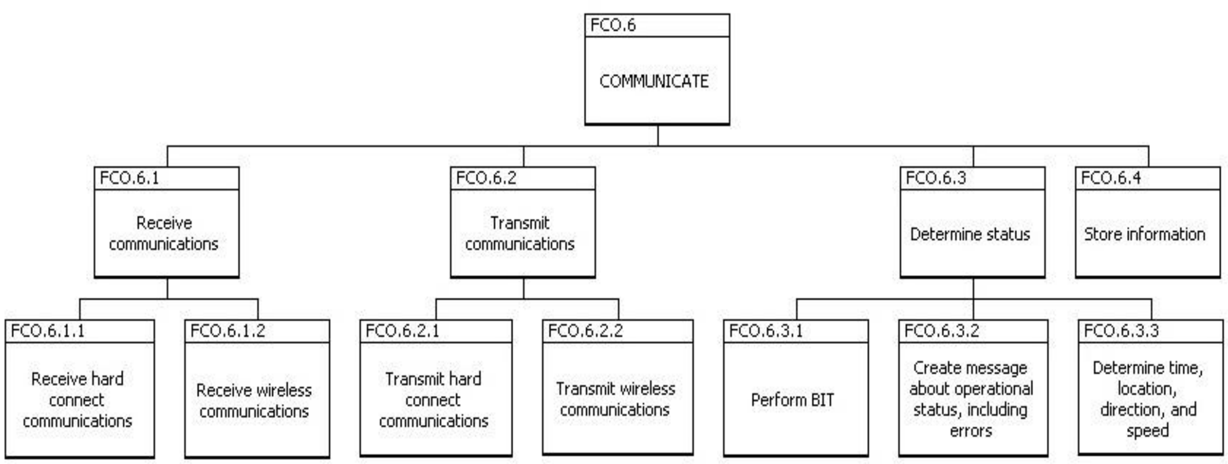

Figure 27. Communicate Function Hierarchy

Functional decomposition of the Communicate function. The Communicate function describes all the functions that are performed when a message is created in other functions. The Communicate function is the link between all the MCM platforms performing the mission and exists throughout the whole mission from start to finish.

k. Receive Maintenance

Figure 28 depicts the functional hierarchy of the receive maintenance function. The receive maintenance function describes events where the MCM platform is under maintenance to support future missions. The maintenance function will assist the system to meet the operational availability and reliability requirements. The receive maintenance function includes five sub-functions:

1. FRM.9.1 Perform maintenance diagnostics
2. FRM.9.2 Receive corrective maintenance
3. FRM.9.3 Receive preventative maintenance
4. FRM.9.4 Receive energy replenishment
5. FRM.9.5 Create message about maintenance status

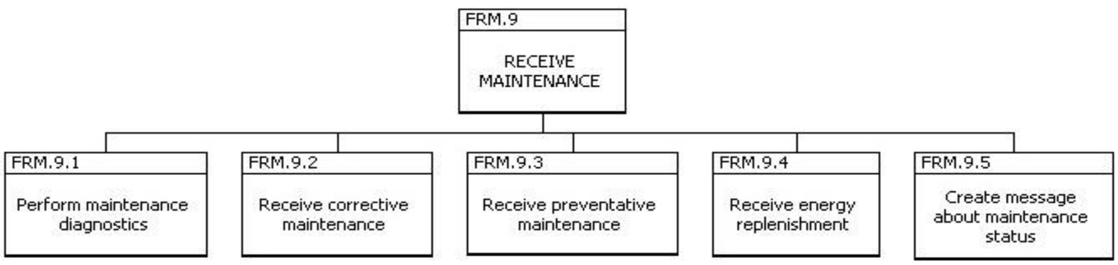

Figure 28. Receive Maintenance Function Hierarchy

Functional decomposition of the Receive Maintenance function. The Receive Maintenance function describes events where the MCM platform is under maintenance to support future missions.

F. MAPPING SYSTEM REQUIREMENTS TO SYSTEM FUNCTIONS

Top level requirements and top level functions were mapped to show traceability and develop initial concepts towards system architectural descriptions. The mapping of requirements to functions, demonstrates the start of the architectural decomposition of the system solution.

		FD.1 - Detect	FC.2 - Classify	FI.3 - Identify	FE.4 - Engage	FT.5 Transit	FCO.6 Communication	FS.7 Search	FDE.8 - Deploy	FRM.9 - Receive Maintenance	FPP.10 - Perform Planning	FR.11 - Recover
REQ 1.0	**Clandestine Operations**	X	X	X	X	X	X	X	X		X	X
REQ 2.0	**Navigation Precision**	X	X	X	X			X				
REQ 3.0	**Autonomous Operational Modes**	X	X	X	X	X	X	X		X		X
REQ 4.0	**Processing Capabilities**	X	X	X	X			X				
REQ 5.0	**MCM Communication**	X	X	X	X	X	X	X	X	X	X	X
REQ 6.0	**Endurance**					X		X	X			X
REQ 7.0	**Operational Environment**					X			X			X
REQ 8.0	**Deployment Distance**					X						
REQ 9.0	**Detection and Classification**	X	X	X				X				
REQ 10.0	**Collaborative Search Patterns**	X	X	X								
REQ 11.0	**Mine Neutralization**	X		X				X				
REQ 12.0	**Multiple Sensors**	X	X	X	X			X				
REQ 13.0	**Electromagnetic Environment**								X	X		X
REQ 14.0	**Reliable and Available**									X	X	
REQ 15.0:	**Launch Platform**					X			X			X
REQ 16.0:	**Minimize Weight, Footprint**								X		X	X
REQ 17.0:	**Weapon Safety**				X							
REQ 18.0:	**Software Architecture**	X	X	X			X	X			X	

Figure 29. High Level Functions Mapped to High Level Requirements

Figure depicts High Level Requirements mapped to High Level Functions for the solution MCM system. The mapping demonstrates that each requirement is implemented by at least one high level function.

G. SYSTEM BOUNDARY

As defined in previous sections of this report, this analysis has identified the complexity and diversity of the VSW zone, defined the requirements and functional attributes necessary for a system operating in the VSW environment. Due to the dynamics of the system scope defined by this cohort team, a decision was made to reduce the problem scope to a manageable effort that would fit within the constraints of our project schedule. Figure 30 describes the bounded system as the shaded area in comparison to the definition of the fully defined system. The scope of the system boundary was chosen to represent the key functions that relate back to the problem statement of addressing the reduction of the DTE sequence in support of amphibious landing operations. It is recommended that functions outside the system boundary are explored by other research.

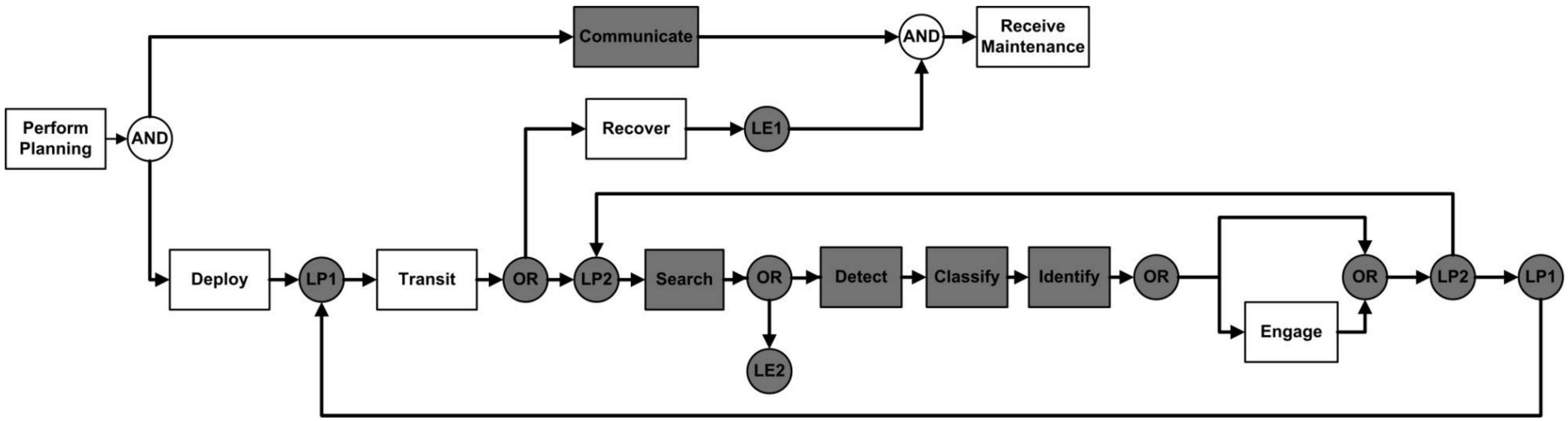

Figure 30. System Boundary

Functional Flow Block Diagram (FFBD) of functions performed by MCM system during a mission conducted in the VSW zone. Shaded functions indicate the system boundary for this report. Shaded functions were examined in depth and with the remaining functions are recommended for future cohort research teams to explore due to the additional complexity and depth of the remaining functions. Walking through the FFBD, the mission starts with the Perform Planning Function. Once Perform Planning is complete, both the Communicate function and Deploy functions start. The Communicate function performs the communications from the MCM system to external systems and is active throughout the duration of the mission, until the MCM system is recovered. After the Deploy function, the first loop, LP1, is entered and the Transit function starts, where the MCM system transits into or out of an operational area depending on direction given by the host platform. With the completion of the transit function, either the Recover function is called to recover the MCM system (if the system has transited to a recovery point), or a second loop is entered to search for mines in the operational area (if the MCM system has transited into a search area). Entering the second loop, LP2, begins the Search-Detect-Classify-Identify sequence. The Search function effectively "mows the lawn" in the operational area looking for mine-like objects. If a mine-like object is detected, the Search function ends and the Detect-Classify-Identify sequence starts for the mine-like object. Once the Identify function has completed, a decision is made whether to engage or not engage the detected mine. Once this decision is made, either the Engage function is called, or it is bypassed. After the Engage function completes or is bypassed, the second loop, LP2, restarts at the Search function, searching the operational area again for a new mine-like contact. LP2 is exited if the MCM system reaches the end of the operational area, or is directed to stop searching during the Search function. This exit of the second loop is noted on the FFBD as "LE2", the loop exit. When LP2 ends, the first loop, LP1, is restarted and the transit function is called again to move the MCM system to a new operational area to further prosecute mines or to a recovery point to recover the MCM system. Once the Communicate and Recovery functions have completed, the Receive Maintenance function is performed at the end of the mission.

IV. ALTERNATIVE ARCHITECTURE DEVELOPMENT

As previously discussed, the boundary of this research is restricted to the scope and function that the MCM system conducts in the operational area during the DTE sequence. Further investigation has proven that even with the scope reduced to the functions of the DTE sequence, the problem is still very complex and challenging to solve due to the many parameters that need to be taken into consideration to develop a solution space. The decision was made to explore the level of autonomy on next generation MCM systems and their effect on meeting the capability gap. Three alternative architectures were developed to further investigate.

A. ALTERNATIVE ARCHITECTURE DEVELOPMENT APPROACH

Our earlier research has shown that the capability gap solutions that had the potential for reducing the DTE were identified as removing the man and mammal from the mine field, removing or reducing PMA, incorporating sensor fusion and extending system endurance. Table 8 displays capability gaps identified as contributors that increase DTE time and developed ideas at providing solutions to bridge the gap. The architecture analysis effort was focused on exploring levels of autonomy, investigating the benefits of real-time data analysis, and recommendations for communication methods, standard sensor packages, and extending endurance.

Table 8. Capability Gaps

This table outlines the capability gaps explored and hypothesized improvements.

<table>
<tr><th>Problem Statement</th><th>Capability Gap</th><th>Capability Gap Solutions</th><th>Capability Analyzed</th><th>Hypothesized Improvements</th></tr>
<tr><td rowspan="10">Reduce DTE</td><td>OTH Capability</td><td rowspan="4">Remove Man/Mammals in the minefield</td><td rowspan="4">Comparison of the 4 Levels of Autonomy</td><td>Reduce burden on humans</td></tr>
<tr><td>Limited Search/Detect/Classify capabilities of MMS and need for UUVs</td><td>Reduction in manning requirements</td></tr>
<tr><td>System Manning Gaps</td><td>As autonomy capability is improved, the DTE timeline is reduced</td></tr>
<tr><td>UUV deployment gap</td><td>Increase in autonomy can enable neutralization</td></tr>
<tr><td>OTH Capability</td><td rowspan="3">Remove/Reduce Post Mission Data Processing/PMA</td><td rowspan="3">Investigate Real-time Communication Networks to support Autonomy architectures</td><td>Real time communications will negate the requirement for PMA</td></tr>
<tr><td>Communication gap with UUVs</td><td>OTH communications allow operators to maintain station on the host platform at a standoff distance from the minefield operation.</td></tr>
<tr><td>UUV on board processing</td><td>Real-time analysis of data (within the UUV)</td></tr>
<tr><td>VSW Sensor Gap</td><td>Incorporate Multiple MCM Sensors
Sensor Fusion</td><td>Standard Sensor Package</td><td>Fuse Sensor Data from Multiple MCM Sensors will increase PdPc in VSW</td></tr>
<tr><td>OTH Capability</td><td rowspan="2">Extend Endurance limitation: Human and System</td><td rowspan="2">Investigate and recommend power systems to support faster, more reliable energy sources that improve ACR</td><td rowspan="2">Ensure system endurance of mission duration</td></tr>
<tr><td>Limited Search/Detect/Classify capabilities of MMS and need for UUVs</td></tr>
</table>

The primary architecture analysis focused on exploring different levels of autonomy and was based on information provided in the Unmanned System Integrated Roadmap 2011-2036 and the Naval MCM UUV Roadmap (February 2011) documents that indicate the progression of future technology is shifting focus of DTE task reliance from humans to unmanned autonomous systems.

The analysis and development of communication networks was derived by investigating the definition of autonomy and the paradigm shift of human control over to decisions being made by autonomous unmanned systems. In order for the humans to transition to the support and monitoring role for autonomous systems, it is necessary to have real time data feedback to a C2 human element in certain architectures. In addition, one of the biggest obstacles with reducing the DTE sequence has been identified by stakeholders and research is the time delay from planning the mission to the time it takes to produce final target location and details.

As discovered through researching capability gaps, system endurance is a limiting factor. The UUV system must transit from a drop point to its AO under different environmental factors that can affect navigation and energy reserves which hinder the ability of a system to complete its mission without the need for refueling or recharging. It is necessary to manage the system power requirements with realistic system power technologies given the previously defined DRMs.

Additionally, the communication system must be able to sustain communication links between the vehicle(s) and the Host Platform for the entire length of the mission. It is necessary to manage and coordinate the communication needs with sustained operations.

B. LIST OF ALTERNATIVES SUMMARY

This section gives a high-level overview of three alternative architectures that were explored. Subsequent sections give further detail for each alternative's unique concepts and configuration.

1. Alternative Architecture One: Fully/Semi-Autonomous System

The main components of Alternative Architecture One are:

a. Fully autonomous Self Propelled Underwater Detection System (SPUDS) vehicle.
b. Fully autonomous over-the-horizon (OTH) buoy communication network.
c. Two person team operating the MCM command and the Host Platform MCM C2 Processing System at the Host Platform.

The main characteristics of Alternative Architecture One are:

a. The vehicle performs navigation functions to include obstacle avoidance without human intervention or guidance from the Host Platform.
b. The vehicle can collaborate between like-vehicles to perform missions without human intervention.
c. The vehicle performs the mission functions of search, detect, classify, and identify.
d. The communication between the SPUDS vehicle(s) and the Host Platform is conducted via a field of communication buoys operating autonomously that convert acoustic communications to RF communications. The buoy field also provides navigation reference points to the SPUDS vehicles in the AO.
e. The MCM Host Platform creates a tactical map of AO based on mine type and mine location information received from vehicles.
f. The Host Platform can control one or multiple SPUDS vehicles without increasing man-power or processing/communication infrastructure.

2. Alternative Architecture Two: Tele-Operated System

The main components of Alternative Architecture Two:

a. Tele-operated SPUDS vehicle.
b. Existing Common Tactical Data Link provided by MH-60 and/or Fire-Scout UAV for OTH C2 and data-linking real time sensor data. Data is transmitted via a tethered floating surface antenna.
c. Six person team operating the Host Platform MCM C2 Processing System at the Host Platform.

The main characteristics of Alternative Architecture Two are:

a. The Host Platform performs navigation functions to include obstacle avoidance by steering the vehicle or giving waypoint guidance.
b. The vehicle cannot collaborate between like-vehicles without human intervention for mission accomplishment.
c. The Host Platform performs the functions of search, detect, classify, and identify through processing real time MCM sensor data arriving from SPUDS vehicles via a data link.
d. The communication between the SPUDS vehicle is conducted via an existing Navy data link system provided by an air platform such as a MH-60 helicopter or a Fire-Scout UAV. The data link is accomplished through the use of the floating tethered antenna.
e. The MCM Host Platform creates a tactical map of AO based on real time mission analysis performed on the Host Platform. This mine type and mine location information is derived by a real time analysis of MCM sensor data streaming from the SPUDS vehicle.

f. The Host Platform can control one or two SPUDS vehicles without increasing man-power or processing/communication infrastructure. The factors that are affected by increasing the number of vehicles are the data-link bandwidth and Navy assistance required to provide real-time processes. Therefore adding additional SPUDS vehicles will require increasing man-power and processing/communication infrastructure.

3. Alternative Architecture Three: Remote/Tele-operated System

The main components of Alternative Architecture Three are:

a. Hybrid Remote-Pilot/Tele-operated SPUDS vehicle that is operated in the AO by a local team.
b. A five person team operating the Host Platform MCM C2 Processing System at the Host Platform.
c. Three person local team to operate the SPUDS vehicle. This local team is in the AO while the MCM Host Platform is operating OTH.

The main characteristics of Alternative Architecture Three are:

a. This system requires a local operator team that operates OTH from the MCM Host Platform. The local operation team consists of 3 people operating a SPUDS vehicle from a small boat in the AO.
b. The local operator performs all navigation functions to include obstacle avoidance by steering the vehicles or giving waypoint guidance.
c. The vehicles cannot collaborate between themselves without human guidance for mission accomplishment.
d. The Host Platform performs the functions of search, detect, classify, and identify through post-mission analysis (PMA) of raw MCM sensor data retrieved from a recording device on the SPUDS vehicle.
e. The communication between the SPUDS vehicle(s) and the local operator is conducted via a new radio data link system that is used to control the vehicle's navigation during mission execution.
f. The MCM Host Platform creates a tactical map of the AO based on the PMA. The mine type and mine location information is derived from the PMA.
g. The Host Platform cannot control SPUDS vehicle. Increasing the number of SPUDS vehicles in the field to perform the mission will increase man-power and processing/communication infrastructure requirements.

C. BASE MCM ADVANCED SYSTEM

Three alternatives architectures were developed in an effort to provide acceptable solutions to the problem. Figure 31 shows same base components that the alternative architectures share. These base components are dubbed the "MCM Advanced System." The MCM Advanced System is composed of three major subsystems which are the UUV System, OTH Communication System, and the Host Platform MCM System. Despite the base system remaining the same among the three architectures, the component's blocks shaded gray in Figure 31 indicate where changes were made between architectures to evaluate each alternative's performance.

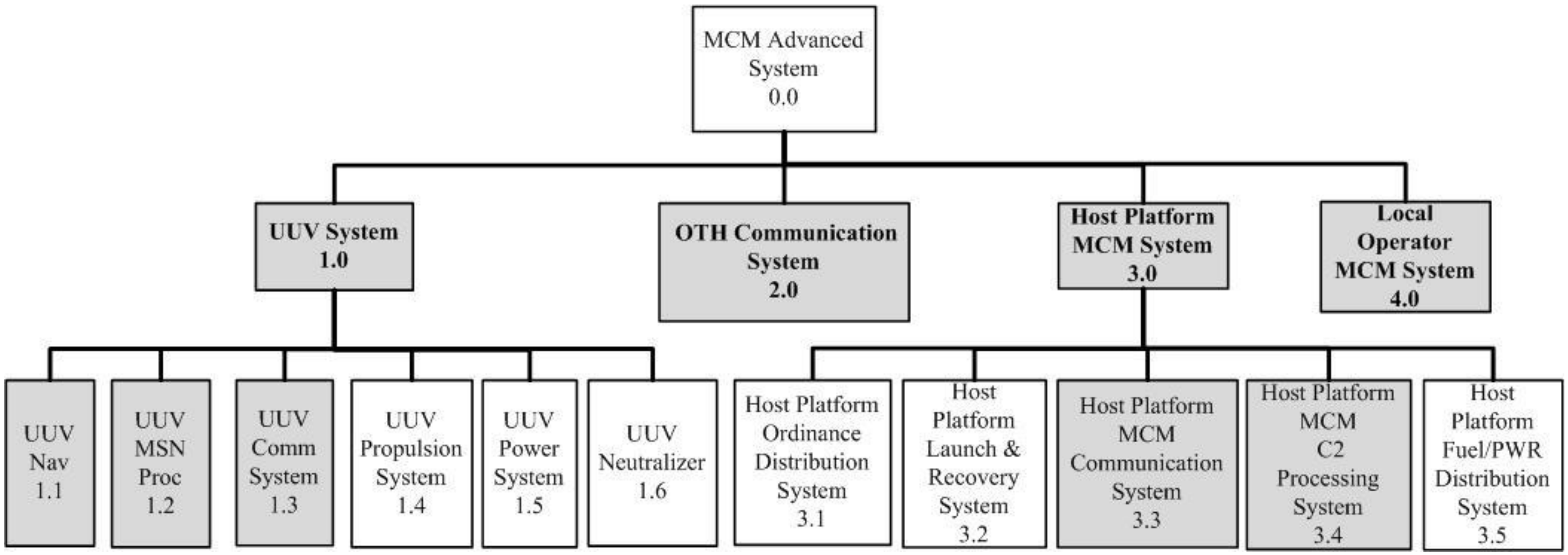

Figure 31. MCM Advanced System Component Diagram

This Diagram depicts the system components of the base MCM Advanced System. Grey shaded components indicate areas that differed in the detailed design of the three alternative architectures.

1. MCM Advanced System Components

The following section details the specific components of the MCM Advanced System depicted in Figure 31.

a. UUV System

The unmanned underwater vehicle system (UUV System) is further detailed by navigation, mission processor, communication, propulsion, power, and neutralizer subcomponents.

UUV Navigation System

The UUV Navigation System is composed of sensor components and computers that enable the UUV to track itself in 3-dimensions during a mission. These components provide heading, 3-dimensional velocity, 3-dimensional acceleration, and depth for all alternatives.

UUV Mission Processor

The UUV Mission processor includes all sensors, components and computers that enable the UUV to process mission critical data and vehicle operation. This includes sensors that are used to search, detect, classify, and identify targets. All three alternative architectures contain the same sensors and components with the exception of optical sensors. However, the number of mission processors and the allocation of functionality for calculating precise coordinates used for tracking vehicle position and mine locations are varied between alternatives. The allocation of search, detection, classification, and identification functionality also vary between the mission processor and the MCM Host Platform for each alternative.

UUV Communication System

The UUV communication system includes the interfaces and components that allow the UUV to communicate in order to execute MCM missions. These components are detailed further in the alternative architecture decompositions.

UUV Propulsion System

The UUV propulsion system includes the interfaces, components, and computers that propel the vehicle through the water. It includes the motors, transmission, steering linkages, fins, and controllers. In this analysis the propulsion system does not vary between alternate architectures.

UUV Power System

The UUV power system includes the interfaces, components, and computers that provide power to the UUV system. The power system includes power monitoring, power regulating, power switching, power generation, and power protection systems. In this analysis the power system does not vary between alternate architectures. It is assumed that the power system provides sufficient power to sustain the power draw of the system during mission execution. The power source is a hybrid power source consisting of a lithium ion battery system with a secondary fuel cell power system to recharge the battery and provide additional boost power when needed. The addition of a fuel cell gives opportunities to refuel the system while in operation and thus sustain or increase its area coverage.

The power consumed by the individual systems was not calculated or estimated in this analysis. It is understood that the power draw of the individual systems can have drastic affects on the type of power generation system needed and the definition of the vehicle architectures. Further study will be needed in the future to determine the power needs of the next generation system.

Neutralizer

The UUV Neutralizer system includes the components necessary to render a mine non-operational. Neutralization could include destroying a mine, neutralizing a mine's ability to detect a vehicle, or detonate a mine to make it inoperable. In this analysis, the focus was maintained on evaluating vehicle systems that would fulfill the searching, detection, classification, and identification functions of the future system. With that caveat, the highest priority for the Marine Amphibious force is to know where the mines are located so that they can be avoided; an effective neutralization method that was used in this analysis.

It is recommended that the neutralization component and function should be allocated to another low cost vehicle. This is because performing neutralization carries the risk that the vehicle performing the neutralization can also become disabled or destroyed when executing a neutralization tactic. This is another area that is recommended for a follow-on in depth study.

b. OTH Communication System

The OTH Communication system includes all the components necessary to allow over the horizon communications between the MCM Host Platform and the MCM vehicle.

Figure 32 shows the expected communication services internal and external to the MCM Advanced System. Although Figure 32 shows the OTH communication system as internal to the

advanced system, this service could be provided by a system external to the MCM Advanced System. The three alternative architectures explored the differences between this communication service provided by a system developed for the MCM Advanced System, or provided by an existing system.

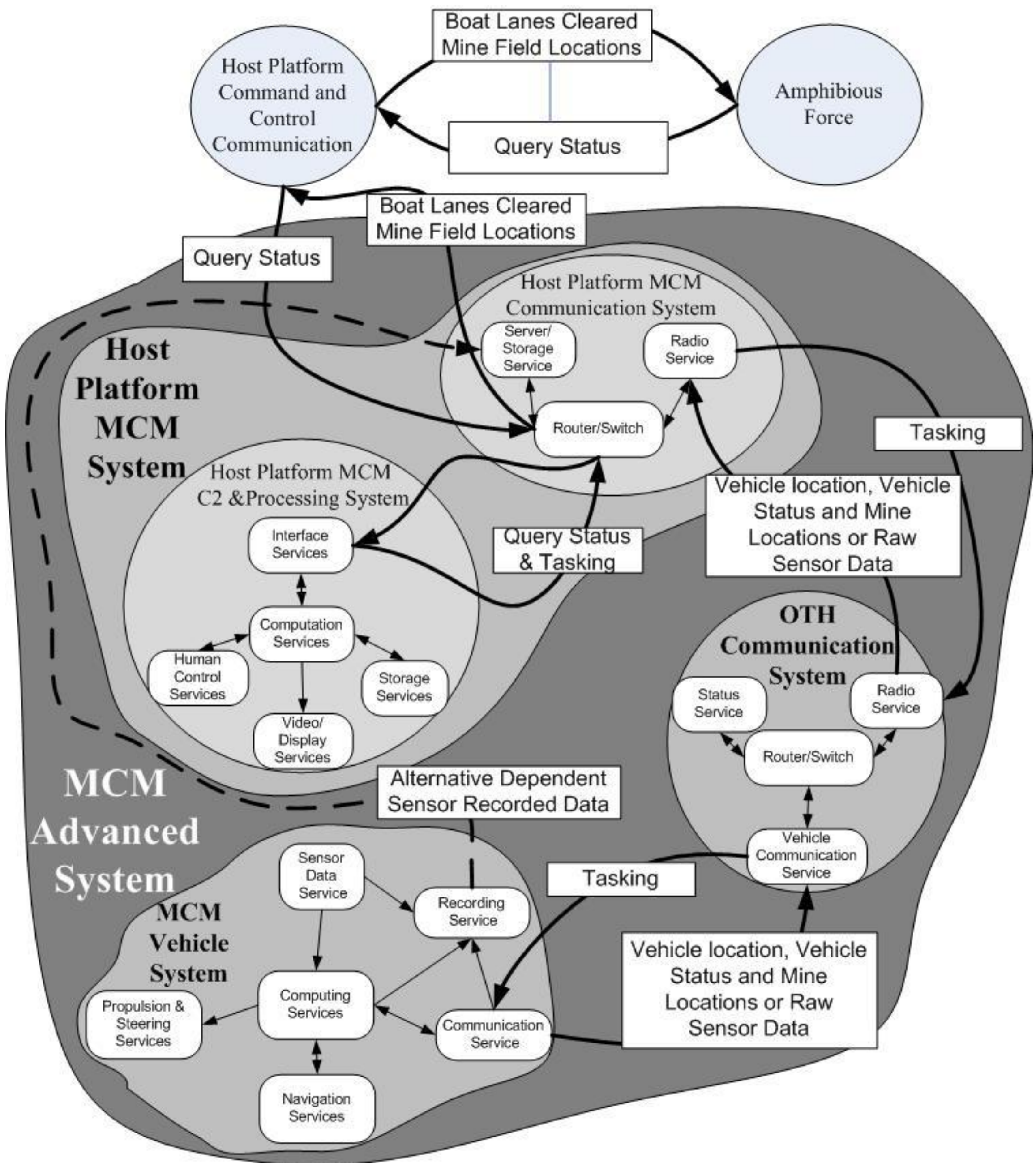

Figure 32. MCM Advanced System Context and Interfacing Diagram

This diagram illustrates the interfaces between system components and the Host Platform's interface with the larger amphibious force.

c. *Host Platform MCM System*

The Host Platform MCM System contains the Host Platform Ordinance Distribution System (HPODS), the Host Platform Launch & Recovery System, (HPLRS), the Host Platform MCM Communication System (HPMCS), the Host Platform MCM C2 & Processing System (HPMC2PS), and the Host Platform Fuel/Power Distribution System (HPFPDS) subcomponents.

Host Platform Ordinance Distribution System

The HPODS system contains the components that store and distribute ordnance aboard the Host Platform. It is envisioned that the neutralizer on the MCM UUV is considered ordnance and will be handled as such. The system needs to handle and store the neutralizer separately from the MCM UUV. The neutralizer component is not addressed in this analysis as previously discussed. It is recommended that another study be developed to investigate impacts and solutions for handling the neutralizer aboard the MCM Host Platform.

Host Platform Launch & Recovery System

The HPLRS system contains the components to safely launch and recover the MCM UUV. This component was not addressed in the alternative analysis and it is recommended that another study investigate the impact and solutions for launching and recovering the MCM UUV aboard the Host Platform.

Host Platform MCM Communication System

The HPMCS contains the components that enable the Host Platform to communicate with the MCM vehicle via the OTH Communication system. The communications between the MCM UUV and the Host Platform are shown in Figure 32 and Figure 33.

Host Platform Command and Control Processing System

The HPMC2PS contains the components that enable the Host Platform to command and control MCM vehicles. It contains the processing for creating tactical overlays of the AO and programs the UUV with routes and guidance. The HPMC2PS pools information from the UUVs to determine where gaps in the mine fields exist, and creates routes for the amphibious force to navigate to the beach. The HPMC2PS also makes neutralization plans based on processed information.

Figure 32 displays the MCM Advanced System context diagram and how the HPMC2PS passes information off the Host Platform Command & Control.

Host Platform Fuel/Power Distribution System

The HPFPDS system contains the components that fuel or store power to the MCM system while it is on the Host Platform. This component is not addressed in the alternative architecture analysis and it is recommended that further study be conducted to investigate the impact and solutions for handling fuel/power for the system while aboard the MCM Host Platform.

d. Local Operator MCM System

The local operator MCM system consists of personnel and components necessary to operate a remote vehicle and to launch and retrieve an MCM vehicle. For architectures that contain remote controlled MCM vehicles, the local operator team is required to be nearby to control the vehicle

2. Host Platform MCM Communication System Sub-Components

Figure 33 depicts the detailed base design of the Host Platform MCM Communication System component. This component was further broken down into shared base components across alternatives because of the complexity of the component. Components shaded gray in Figure 33 indicate components that were changed across alternatives. The following section further details the Host Platform Command and Control Processing System sub-components.

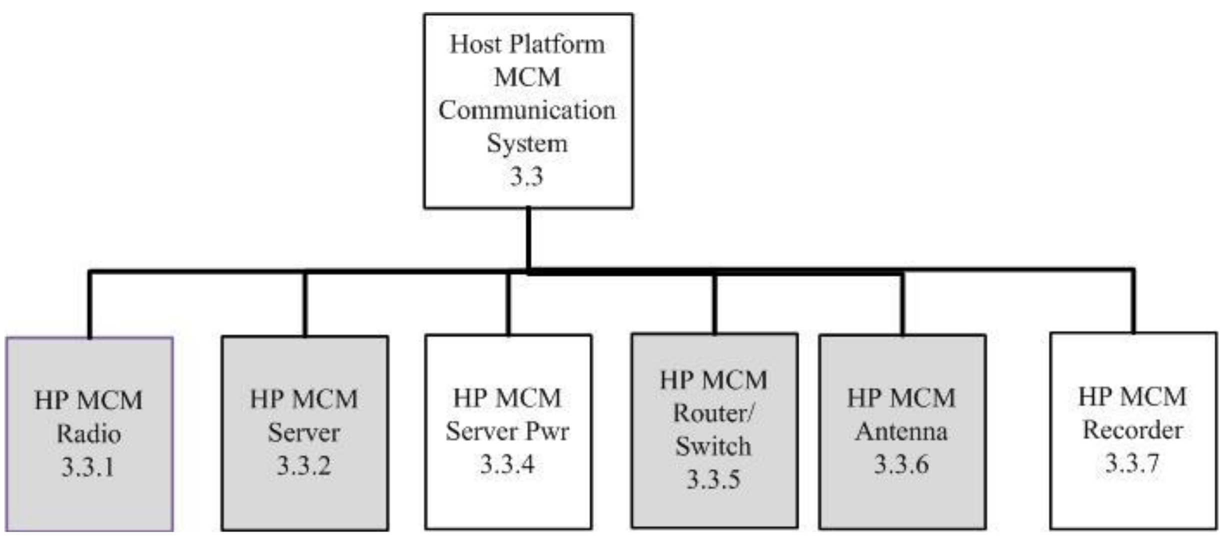

Figure 33. Host Platform MCM Communication System Component Diagram

This diagram depicts the sub-components of the Host Platform MCM Communication System component. Components shaded gray indicated components that varied across alternative architectures.

a. HP MCM Radio

The radio component of the HPMCS varies between alternatives and is dependent on the level of autonomy applied to the architecture. Depending on the level of autonomy the bandwidth of the radio system have been adjusted to accommodate the data needs.

b. HP MCM Server

The HP MCM Server stores, retrieves, and transmits data to the HPMC2PS. Depending on the alternative architecture this component may or may not be part of the system.

c. HP MCM Server Power

The HP MCM Server Power component delivers filtered and surge protected power to the HPMCS. This component was not addressed in this report and it is recommended that another study investigate the impact and solutions for handling the power for the HPMCS.

d. HP MCM Router/Switch

This component routes and enables networking of the Host Platform MCM system. This component varies depending alternative.

e. HP MCM Antenna

This component enables the HP MCM Radio to transmit and receive information from the MCMUUV component. It is considered a separate component from the HP MCM Radio because the component needs to be mounted to the host ship. Depending on the alternative this component may already be part of the Host Platform, or will need to be routed to and mounted in an optimal location. Further study will need to be performed to choose the optimal location for an antenna. Determination of optimal location is outside the scope of this project.

f. HP MCM Recorder

The HP MCM Recorder records all mission parameters in order to be retrieved for further analysis or training. Further study on this component was outside the scope of this project.

3. Host Platform C2 Processing System Sub-Components

Figure 34 depicts the detailed base design of the Host Platform Command and Control Processing System component. This component was further broken down into shared base sub-components across alternatives because of the complexity of the C2 Processing System. The following section further details the Host Platform Command and Control Processing System sub-components.

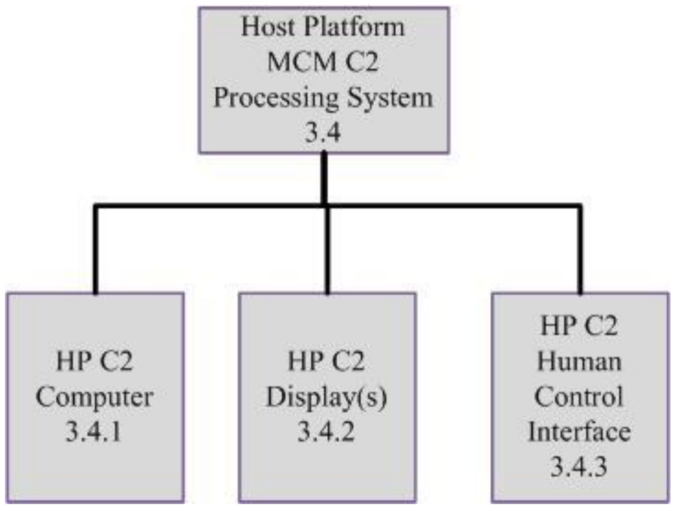

Figure 34. Host Platform Command & Control Processing System

This diagram depicts the components in the Host Platform MCM Communication System. Components shaded gray indicated components that varied across alternative architectures.

a. HP C2 Computer

The HP C2 Computer system processes the incoming data from the MCM UUV. The computer system creates the functionality to command and control the MCM vehicles. It coordinates information with the Host Platform command and control center with the number of computers varying between the alternatives.

b. HP C2 Display(s)

The HP C2 Displays shows MCM vehicle status, maps, tactical symbols, sensor data, and user information to the operators. The number of displays and information varies between alternatives.

c. HP C2 Human Control Interface

The HP C2 Human Control Interface contains all the components that are used to interface the human operator to the MCM system. It contains items such as control panels,

keyboards, mice or trackballs, joysticks and other controls that are used to operate the MCM system. The number and type of interface varies with the different alternatives.

D. FUNCTIONS MAPPED TO SYSTEM COMPONENTS

Table 9 depicts the allocation of the Search, Detect, Classify, Identify, Engage, and Communicate functions to the MCM Advanced System components. It should be noted that Table 9 distinguishes that the allocation is different, depending on the alternative, by designating the letter "A" for alternative. The letter "X" indicates the function is allocated to the component regardless of alternative. The varied components in the mapping correspond to the varied components of Figure 31.

Table 9. Functions Mapped to System Components

This table lists Top Level functions and sublevel function allocated to system components. X= Allocated to all Alternatives, A=Alternative Specific.

Top Level Function	**1st Level Sub function**	**SUB Function**	**System Components**													
			UUV System						OTH Comm System	Host Platform MCM System					Local Operator
			UUV NAV Sys	UUV MSM Proc	UUV Comm Sys	UUV Propulsion Sys	UUV PWR Sys	UUV Neutralizer	Sub Component	Host Platform Ord Distribution Sys	Host Platform Launch & Recovery System	Host Platform Communication System	Host Platform C2 &Processing System	Host Platform Fuel Distribution System	Component
Perform Planning FPP.10	Create Tasking for MCM Assets	FPP.10.1											X		
	Accept Search Plans	FPP.10.2		X									X		
	Accept Tasking from MCM Assets	FPP.10.3		X									X		
	Create Message About Contacts	FPP.10.4		X	X							X			
Deploy FDE.8	Deploy from Sub-surface Craft	FDP.8.1	X	X	X	X	X			X	X			X	
	Deploy from Surface Craft	FDP.8.2	X	X		X	X			X	X			X	
	Deploy from Aircraft	FDP.8.2	X	X		X	X			X	X			X	
Recover FR.11	Recover from Surface craft	FDP.8.3	X	X		X	X				X				
	Emergency Recovery	FDP.8.4	X	X		X	X				X				
Transit - FT.5	Determine Deployment Coordinates	FT.5.1	X	X									A		A
	Determine Path to	FT.5.2	X	X									A		A

Top Level Function	1st Level Sub function	SUB Function	System Components												
			UUV System						OTH Comm System	Host Platform MCM System					Local Operator
			UUV NAV Sys	UUV MSM Proc	UUV Comm Sys	UUV Propulsion Sys	UUV PWR Sys	UUV Neutralizer	Sub Component	Host Platform Ord Distribution Sys	Host Platform Launch & Recovery System	Host Platform Communication System	Host Platform C2 &Processing System	Host Platform Fuel Distribution System	Component
	OA														
	Engage Navigational Sensors	FT.5.3	X	X									A		A
	Engage Transiting System	FT.5.4		X		X	X						A		A
	Transit and Monitor for Obstacles	FT.5.5	X	X		X	X		X			A	A		A
	Acknowledge Entering Search Areas	FT.5.6		X	X										A
	Determine Direction and Dist. to Recov. Pt.	FT.5.7	A	A											A
	Create Msg. Indicating Arrival at Recov. Pt.	FT.5.8		A	A				X			X	X		A
Search - FS.7	Enter OA	FS.7.1	X	X		X	X								
	Activate Search Sensors	FS.7.2		A			X					A	A		A
	Follow Search Commands	FS.7.3		A		X						A	A		A
	Record Platform Location	FS.7.4	A	A	A							A	A		A
	Create Mission Complete	FS.7.5		A					X			A	A		A

Top Level Function	1st Level Sub function	SUB Function	System Components												
			UUV System						OTH Comm System	Host Platform MCM System					Local Operator
			UUV NAV Sys	UUV MSM Proc	UUV Comm Sys	UUV Propulsion Sys	UUV PWR Sys	UUV Neutralizer	Sub Component	Host Platform Ord Distribution Sys	Host Platform Launch & Recovery System	Host Platform Communication System	Host Platform C2 &Processing System	Host Platform Fuel Distribution System	Component
	Message														
	Deactivate Search Sensors	FS.7.6		A			X								A
Detect - FD.1	Receive Info. from Sensors Indicating Contact in Area	FD.1.1		A	A				X						
	Record Location of Contact	FD.1.2		A	A							X	X		A
	Record Environmental Info. From Sensors	FD.1.3		A	A							X	X		
	Create Message about Detection and location	FD.1.4		A	A							X	X		A
Classify - FC.2	Process Sensor Input	FC.2.1		A									X		
	Determine if contact is mine-like or non-mine-like	FC.2.2		A	A							A	A		
	Create message about contact classification	FC.2.3		A	A							A	A		
Identify - FI.3	Determine if Mine like Contact	FI.3.1		A	A							A	A		

Top Level Function	1st Level Sub function	SUB Function	System Components												
			UUV System						OTH Comm System	Host Platform MCM System					Local Operator
			UUV NAV Sys	UUV MSM Proc	UUV Comm Sys	UUV Propulsion Sys	UUV PWR Sys	UUV Neutralizer	Sub Component	Host Platform Ord Distribution Sys	Host Platform Launch & Recovery System	Host Platform Communication System	Host Platform C2 &Processing System	Host Platform Fuel Distribution System	Component
	is a Bottom Mine														
	Determine if Mine like Contact is a Moored Mine	FI.3.2		A	A							A	A		
	Determine if Mine like Contact is a Drifting Mine	FI.3.3		A	A							A	A		
	Determine if Mine like Contact should be Avoided	FI.3.4		A	A							A	A		
	Create message about mine identification	FI.3.5		A	A							A	A		
Engage - FE.4	Create Neutralization Plan	FE.4.1										X			
	Reacquire	FE.4.2		A								A			
	Neutralize Contact	FE.4.3		X				X							
	Create Message About Engagement Results	FE.4.4		A	A				X			X	X		
Communicate	Receive	FCO.6.1		X	X							X	X		A

Top Level Function	1st Level Sub function	SUB Function	System Components												
			UUV System						OTH Comm System	Host Platform MCM System					Local Operator
			UUV NAV Sys	UUV MSM Proc	UUV Comm Sys	UUV Propulsion Sys	UUV PWR Sys	UUV Neutralizer	Sub Component	Host Platform Ord Distribution Sys	Host Platform Launch & Recovery System	Host Platform Communication System	Host Platform C2 &Processing System	Host Platform Fuel Distribution System	Component
– FCO.6	Communications														
	Transmit Communications	FCO.6.2		A	A							X	X		A
	Determine Status	FCO.6.3		X								X	X		A
	Store Information	FCO.6.4			X							X	X		
Receive Maintenance - FRM.9	Perform Maintenance Diagnostics	FRM.9.1		X	X	X	X	X	X	X		X	X		A
	Receive Corrective Maintenance	FRM.9.2		X	X	X	X	X		X		X	X		A
	Receive Preventative Maintenance	FRM.9.3				X	X	X		X	X			X	
	Receive Energy Replenishment	FRM.9.4		X		X								X	A
	Create Message about Maintenance Status	FRM.9.5		X	X							X	X		A

E. REQUIREMENTS MAPPED TO SYSTEM COMPONENTS

Table 10 depicts a mapping of requirements to MCM system components. Table 10 distinguishes that the allocation is different, depending on the alternative, by designating the letter "A" for alternative. The letter "X" indicates the function is allocated to the component regardless of alternative. More details regarding each alternative can be found in Appendix E.

Table 10. MCM Advanced System Components Mapped to Requirements

This table lists system requirements allocated to system components. X= Allocated to all Alternatives, A=Alternative Specific

	MCM Advanced System											
	UUV System						OTH Comm. System	Host Platform MCM System				Local Operator
System Requirements mapped to System Components	UUV Navigation System	UUV Mission Processing System	UUV Communication System	UUV Propulsion System	UUV Power System	UUV Neutralizer	Communication Link	Host Platform Launch & Recovery	Host Platform MCM Communication System	Host Platform MCM C2 & Processing System	Host Platform Fuel/Power Distribution System	Local Operator MCM System
REQ 1.0: Clandestine Operations	A		A	X	X	X	A	A	X	A		A
REQ 2.0: Precise Navigation	A	A	A	X			A		A	A		A
REQ 3.0: Autonomous Operational Modes	A	A	A				A		A	A		A
REQ 4.0: Processing Capabilities	A	A	A				A		A	A		A
REQ 5.0: MCM Communication		A	A				A		A	A		A
REQ 6.0: Endurance	A	A	A	X	X		A		A	A		
REQ 7.0: Operational Environment	X	X	X	X	X	X						
REQ 8.0: Deployment Distance	A	A	A	X	X	X	A	A	A		X	A
REQ 9.0: Detect and Classify Mines		A	A				A		A	A		A

Note: Requirements REQ10.0 through REQ 18.0 are not included in the analysis because they are not differentiators in the discrimination of the alternatives.

1. MCM Advanced System Components for Clandestine Operations

To design the Advance MCM system to meet the clandestine operational requirements, the requirements have been allocated to the system components as shown Table 10 for special design considerations for the following reasons:

a. If the navigation system components are not precise enough, they will demand more human intervention. It would also require the UUV to surface more often to correct for navigation errors and thus be exposed for observation. This concept has been explored further through modeling and simulation and is detailed later in this report.

b. The communication network and functionality can affect the ability of being detected by the number of communication attempts and method of communication with the vehicle. If the communication network has a design with floating antennas, they could be detected by observation from the shore. If the communication network has a large electromagnetic transmission, it could also be picked up, monitored and can give away system movement data. This concept has been explored further in establishing communication networks for the individual architecture.

c. The propulsion system of the vehicle can affect the UUV's ability to be clandestine by creating noise that can be detected.

d. The power system of the vehicle can affect the ability of detection by not having sufficient endurance. This creates the demand for human intervention to recover or refuel the vehicle and thus be exposed to detection.

e. The neutralizer component can give away intentions by pre-maturely detonating mines that are within observation from the shore, thus giving away the intentions of the landing force.

f. The launch and recovery of MCM vehicles from the Host Platform can compromise the detection of the vehicle. For example the MCM vehicle could be observed when launched from a surface platform or dropped from an air platform. However, the system may not be detected when it is launched from a subsurface platform, or when it is launched from an air or surface platform during times of limited visibility. This report further suggests ways the vehicles can be launched, however, it does not go into depth on this subject as this area is beyond the scope of this report and is recommended for further investigation.

2. Navigation Requirement vs. System Components

The MCM vehicle navigation sensors, computers, and propulsion system can affect the ability of the vehicle to track its heading, speed, velocity, acceleration, and latitude and longitude position. The alternatives explored different ways the vehicle achieves navigation requirements while propulsion remains the same for all alternatives. The communication system impacts the navigation for some of the alternatives since it is used to aid the navigation system. It is imperative the Host Platform tracks the navigation results to plot mine contacts and vehicle status.

3. Operational Mode Requirements vs. System Components

The ability to perform autonomous operations has been allocated to the navigation systems, processors, and communications systems of the Advanced MCM system. It is has been observed and noted from subject matter experts that the ability to process information and communicate has a direct effect on autonomous behavior. The navigation system has been allocated to operation mode requirements because it directly affects the MCM system's ability to make decisions. A system with a poor navigation solution cannot operate with a high level of autonomy and would require human intervention. Therefore the alternative architectures explored different levels of autonomy and how it affects the overall system performance.

4. Processing Capability Requirements vs. System Components

The processing capability is allocated to the computer systems of the alternative architectures. However, processing is also allocated to the communication system. The communication and navigation systems have a direct effect on supplying information that must be processed for creating target reports and vehicle status information.

5. Communication Requirements vs. System Components

The processing capability is allocated to the computer systems, communication systems and command and control systems of the alternatives. The different alternatives with different levels of autonomy are explored to show the effects on these components.

6. Endurance

Endurance is affected by the body shape, propulsion system and power system of the vehicle. However, the navigation and processing system can affect the system endurance by optimally steering and adjusting the speed of the vehicle to increase its endurance. The different alternatives were assessed for endurance through modeling and simulation and are discussed in later sections of this study.

7. Operational Environment vs. System Components

All the components of the MCM vehicle are affected by the operational environment. However, the alternative architecture analysis did not evaluate the effects of the environment on the components.

8. Deployment Distance Requirements vs. System Components

Presenting solutions to satisfy deployment distance requirement is outside the stated functional boundaries and were not analyzed further in the report. However, components that affect this requirement are given here for future consideration:

a. Propulsion System, Power System, and Deployment Point. It is assumed that the deployment point for the vehicle may be in the area of interest (AI) but not in the AO. If the power system cannot support the power draw of the system while the vehicle transits from the deployment point to the AO and conducts its mission, the distance from the deployment point to the AO must be shortened.

b. Communication system does not support the operation of the vehicle. If the communication system does not support the communications between the vehicle and the Host Platform because the vehicle is out of communication range, the distance between the vehicle and the Host Platform must be shortened.

c. Navigation error. If error builds up in computing the navigation solution while the vehicle transits to the AO, the deployment distance must be minimized to support navigation offset requirements.

9. MCM Mission Requirements vs. System Components

The system components consisting of processing systems and communication systems affect the Advanced MCM System's ability to detect and classify mines. It affects the ability to perform collaborative searches within the AO. The alternatives architectures explored different options to meet these requirements.

F. STANDARD VEHICLE CONFIGURATION

The capability gaps explored were conducted assuming a standard vehicle system architecture description with variations on the configuration of components to enable autonomy and real time communication networks. This scope was chosen to also not repeat previous research and to take a path that was not yet explored. A standard vehicle description enabled a focus on exploring the technological demand that will be needed in the 10 to 15 year range to successfully field the system.

The main UUV system for the Advanced MCM System is the Self Propelled Underwater Detection System, or SPUDS. The concept of SPUDS is to create a vehicle that maintains the envelope of a MK-46 or MK-50 lightweight torpedo while stored in a pre-launch state. Keeping the standard vehicle within this envelop offers several advantages, of which, the primary advantage is interoperability. The SPUDS vehicle enables aircraft and ships that are configured to launch and store torpedoes to be able launch the SPUDS vehicle with little or no modification or additional testing. Figure 36 and Figure 37 show the physical envelop of the SPUDS vehicle which is identical to the MK-50 torpedo dimensions.

Several other advantages were realized in using a torpedo shape. The dimensions of the MK-46 and MK-50 lightweight torpedoes provide a familiar configuration for existing modeling, simulation, and analysis tools. Altering the physical shape and size significantly from this would cause other factors that would then have to be considered during the alternatives analysis. These factors could potentially be integration with a Host Platform, an increased logistical footprint, and changes in vehicle speed and endurance that could be achieved with a larger vehicle storage space for fuel. It was also decided that the size of the underwater vehicle should be limited in size due to the need to be able to carry out operations in the VSW area necessitating a small to mid-sized platform. Additionally, keeping the vehicle weight and center of gravity within the envelope of the Mk-46 and Mk-50 allows standard bomb racks such as the BRU-14 found on MH-60 helicopters to launch the vehicle. It should also allow the program to skip captive carry and jettison testing on the MH-60R, SH-60B, and P-8 air platforms.

Technological assumptions made for the future SPUDS platform include:

a. Ability to fuse data from multiple sensors and subsystems (Data fusion)
    - This would allow the system to be able to combine data from multiple navigation and sensor components to provide more accurate positional and threat data than one component alone could provide. SPUDS sensor data could be combined together and analyzed to increase the probability of detection and correct classification.

b. Increase in the endurance ability of battery cells

c. Use of the communication network for higher bandwidth data transfer and longer distance communications.

1. **Standard Vehicle Details**

A depiction of the overall system's physical form is shown in Figure 35. The vehicle should comply with the physical characteristics that the electric motors (as shown in Figure 35) would have to be retractable within the envelope of the system in its pre-launch state. The same is true with stabilization fins, as these would also have to be equipped with a retraction feature. Any sensors would also have to be able to fit within the envelope.

Figure 36, Figure 37 and Figure 39 further shows more details of the SPUDS vehicle. It is envisioned that this vehicle can be launched from a variety of platforms and thus enable it to be seeded into the AO by subsurface, surface or air platforms. The vehicle should weigh no more than 798 lb max. This weight is derived on the weight of the Mk 46 or Mk-50 torpedo.

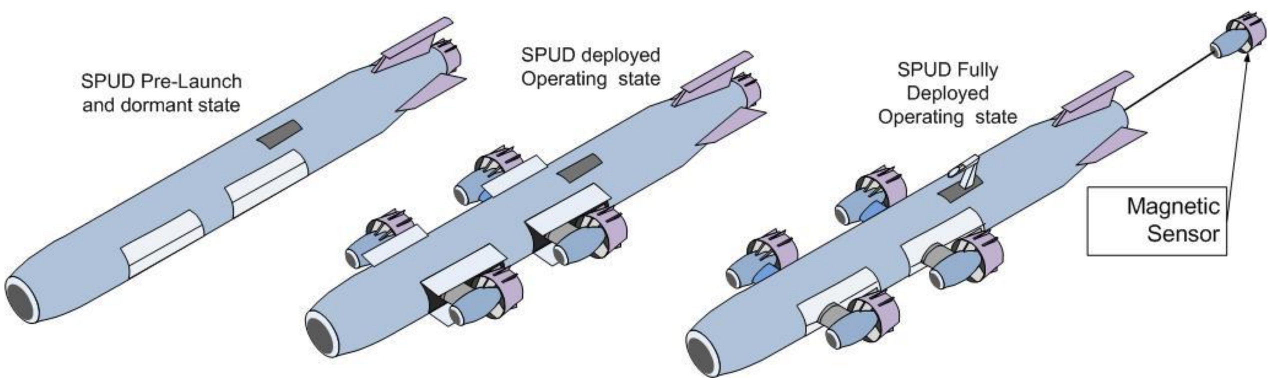

Figure 35. SPUDS Deployed States

This figure depicts the SPUDS vehicle's different operational states.

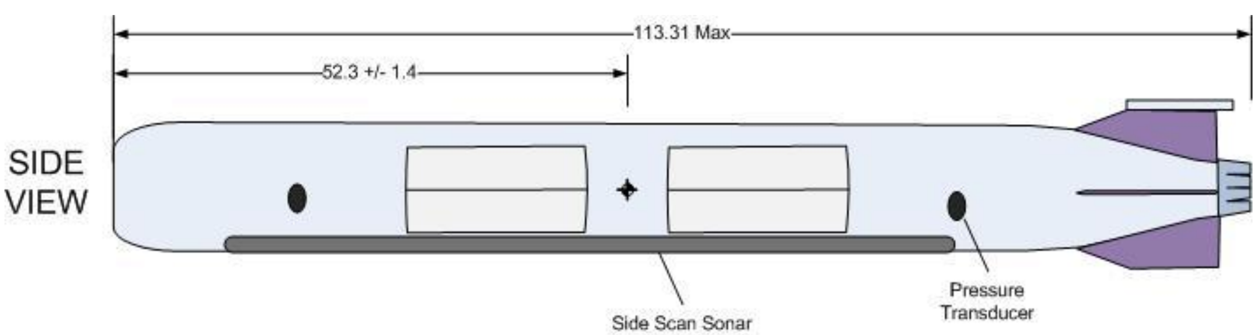

Figure 36. SPUDS Pre-launch Side view

SPUDS Side View concept.

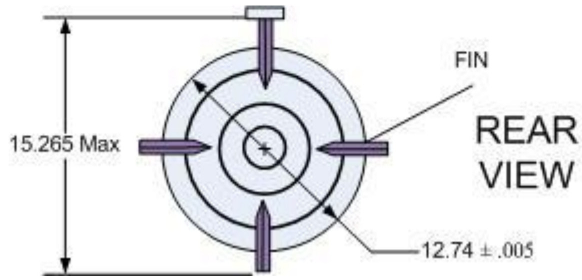

Figure 37. SPUDS Pre-launch Rear View

This figure shows the envelop dimension of the SPUDS vehicle in the prelaunch state. The prelaunch dimensions are essentially the same as a MK-46 torpedo allowing stowing in already existing torpedo racks.

Figure 38 shows the recommended launch envelop for the SPUDS vehicle that was derived from the configuration control drawing for the MK-50 torpedo (Torpedo MK50 Configuration Drawing, 1982). The vehicle should be designed to be no less rugged than the Mk50. In other words, it should be rugged enough to be launched from a surface vehicle using rocket assisted launch, much the same as an Anti-Submarine Rocket (ASROC) or dropped from air platform such as a P8 or MH-60 helicopter. It should be noted here that an argument can be made that an air launched or rocket delivered SPUDS vehicle will compromise the stealth or clandestine operation requirement (REQ 1.0). In the case of a rocket assisted or air launch, the standoff distance of the taskforce can be greatly increased while still allowing the SPUDS vehicle to transit undetected to the AO when it reaches a certain drop point.

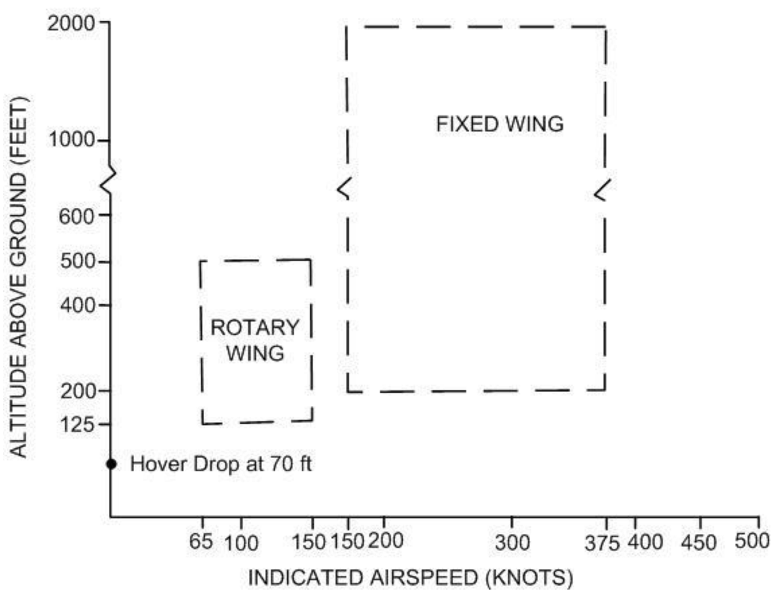

Figure 38. Launch Envelop for SPUDS vehicle

The figure above shows the launch envelop that is applicable to the SPUDS vehicle.

Considering that employment of deception is a core fundamental to US military doctrine for amphibious breaching operations, the employment of less stealthy launch options such as surface, air, or rocket assisted launches are viable (Joint Publication 3-02, 2009). SPUDS can be delivered into the AO when US forces are conducting activities such as bombing or cruise missile attacks during hours of limited visibility and remain dormant until needed. Even if a SPUDS vehicle is observed entering the water during such an activity; it can be misinterpreted as a weapon system malfunction and thus mask its real intended purpose. Again the argument could be made that a bombing raid will alert the enemy that something is coming. However, US forces conduct bombing raids for a number of reasons to include deception. A bombing raid does not necessarily signal or pin point a location where an amphibious operation is going to take place. Ideally the best way to insert the SPUDS vehicle into the AO is to insert the vehicle via a submerged platform, such as a submarine. However, if this is the only way to insert the vehicle; it limits the options for the Navy/Marine Corp team and takes away a much needed flexibility.

Another argument can be made that a SPUDS vehicle cannot be made to survive an air delivery or rocket assist delivery system. However, again we must consider the MK46 or MK50 torpedo, from which this concept is derived. The torpedo is an example of an autonomous vehicle with a much older technology that is able to survive these types of delivery systems. Therefore, the Navy should considered challenging industry to build a vehicle that can be inserted multiple ways to include rocket assist and air dropped deliveries systems.

The pre-launch state of the SPUDS vehicle as shown in Figure 36 and Figure 37 allows it to be configured for rocket assisted launch. When using the rocket assisted launch configuration, the vehicle is designed with a parachute deployment mechanism that allows a water entry velocity of 150 ft/sec at 90 degrees. The parachute decelerates the vehicle from a speed of 800 ft/sec to 150 ft/sec. Once the vehicle transitions from prelaunch state to operational state it extracts its motors out of the housing as shown in Figure 39. The motors are speed variable, reversible, and, independent to allow for steering and maneuverability.

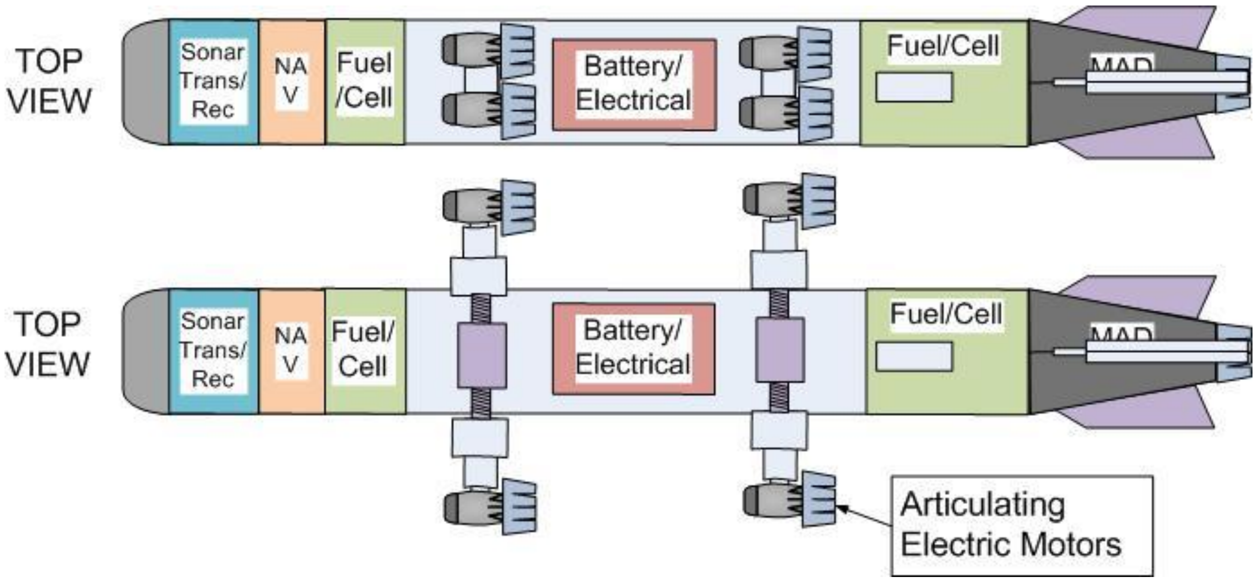

Figure 39. SPUDS Top View Showing Conceptual Layout

This figure shows the conceptual physical configuration layout of the SPUDS vehicle.

It is expected that the endurance and speed of the SPUDS is at least that of the most current version of the MK18 UUVs. Although this investigation has not performed a power analysis to confirm or deny that the SPUDS vehicle power system supports the number of components for the expected endurance, the assumption was made that technological developments will, in the next 10-15 years, allow the SPUDS vehicle to achieve these levels.

2. SPUDS General Component Solutions

Table 11 provides a general overview of the component solutions that were used in the standard SPUDS architecture. This section further details the general systems of the base SPUDS vehicle.

Table 11. SPUDS Architecture Components

Table 11 describes the various component solutions to the standard SPUDS physical architecture.

SPUDS Architecture Components		
Component	**Sub Component**	**USE**
Navigation	Temperature Sensor	Temperature used to calculate speed Depth and speed of sound
	Inertial Navigation System	Provides Heading, Speed, 3-dim velocity, 3-dim acceleration, and Lat/Long
	GPS	Provides Heading, Speed, 2-dim velocity, 2-dim acceleration, and Lat/Long
	Doppler Velocity Log	Provides Speed, Heading, Velocity
	Pressure/Depth Transducer	Used to calculate Depth
Mission Processing	Mission Processor or Interface Box	Used to calculate mission profiles
Communications	Radio	Used to communicate above water
	Acoustic Communication Device	Used to Communicate below water
	Recording System	Used to record mission parameters and sensor data
Propulsion	Engine	Has 4 DC reversible engines that articulate used to propel vehicle through water
	Steering/Retraction System	Used to extend/retract engines into body. Also articulates engines for steering
	Engine Controller	Controls DC power to engines.
Power	Battery	Primary Power source for vehicle
	Power Generator	Secondary Power source for vehicle
	Power Switch Controller	Used to control On/Off power for vehicle
Sensors	Magnetometer Sensor(s)	Used to detect metal bottom and buried mine like objects
	Magnetic Controller Processor	Used to preprocess magnetic signals and control reeling machine
	Magnetic Real Machine	Extend Magnetic Sensors away from vehicle body.
	Optical	Used to detect moored and bottom mines.
	Fwd Looking Sonar	Used to detect moored mines
	Right Scan Sonar	Used to detect Moored and bottom mines
	Left Scan Sonar	Used to detect Moored and bottom mines

a. VSW Sensor Package

The MCM sensor package as shown in Table 11 for the SPUDS vehicle is the same for all alternatives with a few minor exceptions. Since in the VSW environment it is extremely difficult to detect and classify mines, the SPUDS vehicle employs multiple sensors to search, detect, classify, and identify mine-like objects. The SPUDS vehicle contains real-time tracking magnetic gradiometers and laser scalar gradiometers to provide capabilities to map bottom and buried targets. SPUDS contains forward looking and side scan sonar to search, detect, classify, and identify moored and bottom targets. Multiple electro-optical sensors with infrared (IR) illumination provide SPUDS with situational awareness (SA) and identification capabilities. The different alternatives further explored different methods of processing raw data, looking into the difference between on-board and off-board data processing. Table 12 contains the general subcomponents of the SPUDS sensor package.

Table 12. SPUDS Sensor Package

This table shows the standard MCM sensor package on the SPUDS Vehicle.

Sensor System	Subcomponents	Number
Magnetic Gradiometer System	One Extendable Sensor Cluster containing Magnetometer Sensors	3 Magnetometer Sensors
	Reeling Machine for Magnetic sensor	1
	Magnetic Controller Processor	1
Sonar System	Fwd Sonar Transducer	1
	Side Scan Sonar	1
Optical System	CCD/LED (LED will provide illumination)	Alternative Dependent

b. Propulsion System

The propulsion system of the SPUDS vehicle consists of four DC electric reversible motors and is standard for all three alternative architectures. This report does not address the size of the electric engines. However, the engines should not be able to draw no more than 2 amps at startup and should create 1.2 horsepower at peak. The propulsion system has a motor controller to regulate the individual motor speeds and the directional spin (clockwise/counter-clockwise) of each individual motor. The motor controller also directs the steering/retraction system. The steering/retraction system extends or retracts the motors from the SPUDS body. It also articulates the motors to provide steering. The motors are fitted with a propeller and shield to protect the propeller during operation.

c. Power Distribution System

The power distribution system is composed of a battery unit, power generator system, and power switch controller. The battery is the primary source of power for SPUDS, consisting of rechargeable Li-Ion batteries, or Li-Poly batteries. The power system also contains a power switch controller to turn on and off systems and to regulate power usage. This system must be able to communicate with mission processors for vehicle status and power management.

A Fuel Cell Energy/Power System (FCEPS) augments the battery system with a refuel-able charger to extend the endurance of the SPUDS vehicle. Although fuel cell technology is not ready today to provide power for UUVs, the technology is plausible in the 10-15 year timeframe because of current commercial economic pressures to further develop electric and hybrid cars. In a report by the Hawaii Natural Energy Institute, it was indicated that the FCEPS look promising for near-future UUV applications (Davies & Moore, 2006). Further research should be conducted into covertly refueling or recharging the SPUDS vehicle while underway to sustain its endurance as this was outside the scope of this project.

d. Neutralization

In an effort to propose a potential solution for the neutralization architecture, the following high-level concepts are recommended to accomplish the neutralization task:

1. Map and Avoid the Mine: A mine is effectively neutralized if its location is known and it can be avoided. The tactical oversight will be responsible for developing a map showing locations of mines and routes around or through them. This tactical map must be communicated to the amphibious force which will assign routes to individual landing craft vehicles. The vehicles must have the ability to navigate the routes precisely with navigational aids originating inside the amphibious vehicles.
2. Develop a low cost vehicle to neutralize the mines: In some instances, it may not be possible to avoid the mines. It is recommended that a separate expendable UUV with search and detect abilities should be considered for neutralization. The constraints and potential adverse effects of the neutralizers (jamming, explosions, and battery drainage) on the UUV could be catastrophic. As a result, a secondary vehicle is recommended to perform the neutralization. In this case, SPUDS would have to be equipped with the ability to direct and even control the secondary vehicle, especially in the case of a fully autonomous system. Neutralization in this case can be performed several ways. The first option would be in the form of mini "torpedoes" that could be launched at the target. A second option would be to use electronic warfare (EW) technologies to jam or disable the mine fuse or mine sensor via an expendable vehicle that would be equipped with jamming or electromagnetic disabling technology. A third option of neutralization would use deflagration. Deflagration is achieved when propellant, thermite, pyrotechnic, or

solid reactive materials penetrate a mine's case and burn the mine's main explosive charge (Institute for Defense Analyses, 2005).

3. Use existing assets to neutralize mines: Once routes have been determined from the area mapping, a precise targeted mine field location can be communicated to forces with neutralization assets. For example the targeted mine field location can be communicated to Air Force or Navy assets that can drop JABS munitions to achieve neutralization.

Due to the limited timeframe and focus of this project, developing mine neutralization methods was considered outside the scope of this project. Undersea mine neutralization is a complicated and intricate subject to study and will need further attention in future efforts.

G. LEVELS OF AUTONOMY

To remove the man and mammal from minefield operations, future MCM vehicles must be designed to operate with some level of autonomy. The National Institute of Standards & Technology (NIST) defined various levels of autonomy in Special Publication 1011(NIST, 2004). It defined autonomous as

> Operations of unmanned systems (UMS) wherein the UMS receives its mission from the human and accomplishes that mission with or without further Human-Robot Interaction (HRI). The level of HRI, along with other factors such as mission complexity and environmental difficulty, determine the level of autonomy for the UMS (NIST, 2004).

There are four levels of autonomy in UMS which include: Fully Autonomous, Semi-autonomous, Tele-operation, and Remote Control. In this report, systems that were explored as recommended solutions for the problem statement are Fully Autonomous/Semi-Autonomous (Alternative One), Tele-operated (Alternative Two), and Tele-operated/Remote Controlled (Alternative Three).

Table 13 shows definitions for autonomy in relation to unmanned systems. The first set of definitions comes from the Unmanned System Integrated Roadmap FY 2011-2036 (Unmanned Systems Integrated Roadmap FY2011-2036, 2011), and the second from NIST Special Publication, Autonomy Levels for Unmanned Systems (ALFUS) Framework (NIST, 2004). For this report, both definitions were used since the Unmanned Systems Integrated Roadmap definition related to a more human-based definition and the NIST Special Publication definition relates more to the system aspect. It is important to use both of these definitions because considerations for autonomy should include the role of the human and the system. Appendix D further details considerations for implementing different levels of autonomy in an MCM system.

Table 13. Levels of Autonomy

The table compares definitions of autonomy from the Unmanned Systems Integrated Roadmap to definitions by NIST Special Publication (Unmanned Systems Integrated Roadmap FY2011-2036, 2011; NIST, 2004): Autonomy Levels for Unmanned Systems. It is important to understand the approach of each definition and the relationship of the human for each level of autonomy.

Level of Autonomy	Unmanned System Integrated Roadmap (2011-2036)	NIST Special Publication, Autonomy Levels for Unmanned Systems (ALFUS) Framework
1	**Full Autonomous**	**Fully Autonomous**
	The system receives goals from humans and translates them into tasks to be performed without human interaction. A human could still enter the loop in an emergency or change the goals, although in practice there may be significant time delays before human intervention occurs.	This is a mode of operation of an unmanned system (UMS) wherein the UMS is expected to accomplish its mission, within a defined scope, without human intervention. Note that a team of UMSs may be fully autonomous while the individual team members may not be due to the needs to coordinate during the execution of team missions.
2	**Human Supervised**	**Semi Autonomous**
	The system can perform a wide variety of activities when given top level permission or direction by a human. Both the human and the system can initiate behaviors based on sensed data, but the system can do so only if within the scope of its currently directed tasks.	A mode of operation of an Unmanned system (UMS) wherein the human operator and/or the UMS plan(s) and conduct(s) a mission that requires various levels of human-robot interaction (HRI).
3	**Human Delegated**	**Tele-operated**
	The vehicle can perform many functions independently of human control when delegated to do so. This level encompasses automatic controls, engine controls, and other low-level automation that must be activated or deactivated by human input and must act in mutual exclusion of human operation.	A mode of operation of a Unmanned system (UMS) wherein the human operator, using video feedback and/or other sensory feedback, either directly controls the actuators or assigns incremental goals, waypoints in mobility situations, on a continuous basis, from off the vehicle and via a tethered or radio linked control device. In this mode, the UMS may take limited initiative in reaching the assigned incremental goals.
4	**Human Operated**	**Remote Piloted**
	A human operator makes all decisions. The system has no autonomous control of its environment although it may have information-only responses to sensed data.	A mode of operation of a Unmanned system (UMS) wherein the human operator, without benefit of video or other sensory feedback, directly controls the actuators of the UMS on a continuous basis, from off the vehicle and via a tethered or radio linked control device using visual line-of sight cues. In this mode, the UMS takes no initiative and relies on continuous or nearly continuous input from the user.

H. ALTERNATIVE ARCHITECTURES

1. Alternative One

The Alternative One solution revolves around the concept that the MCM force deploys fully autonomous systems and activates them upon the start of MCM mission. The fully autonomous systems can be launched from multiple platform types and lie dormant until the MCM Host Platform arrives on station. It is envisioned that the Host Platform is a littoral combat ship and that Alternative One makes up a MCM mission module for the ship. The ship (or Host Platform) monitors and assigns tasking to an underwater vehicle (UUV) via acoustic/radio signals as shown in Figure 40.

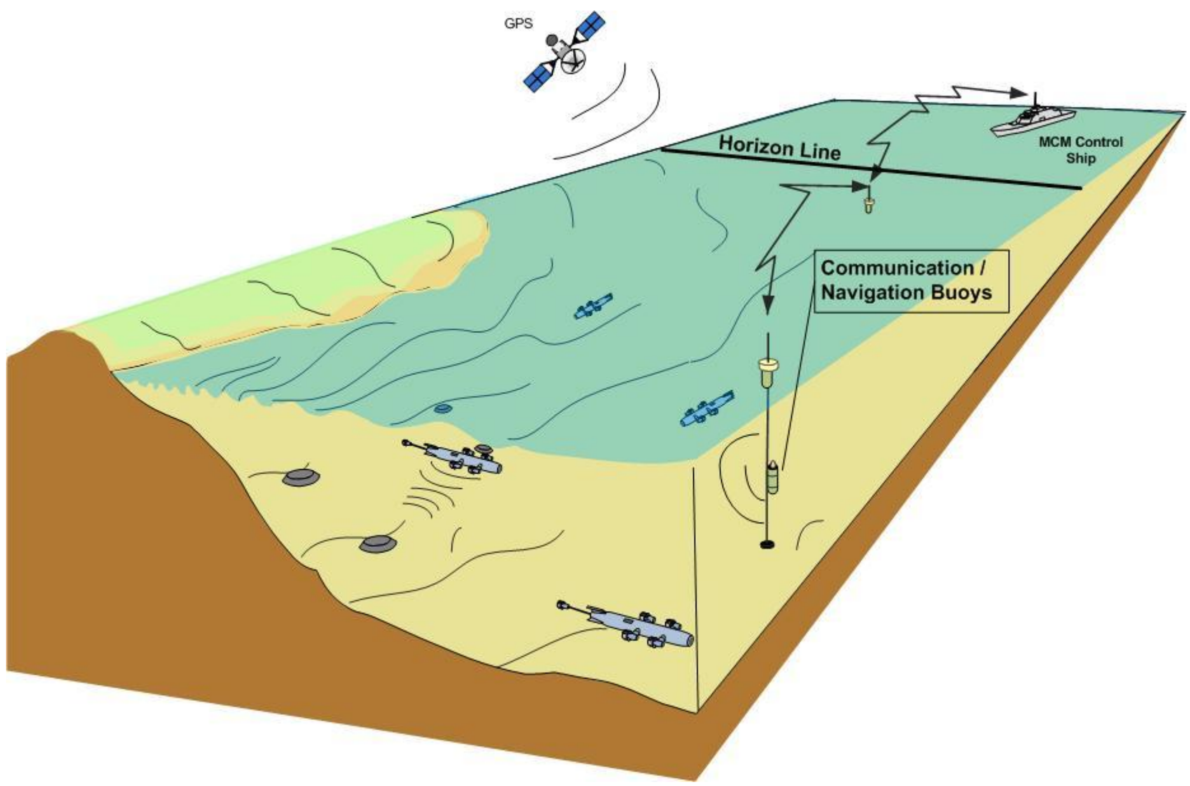

Figure 40. Alternative One: Operational Concept

This figure depicts the operational concept of Alternative One derived from (Freitag, 2005). The underwater vehicle relays search information back to a MCM ship using a surface-tethered radio link. The data is first transmitted to an air platform, and then relayed back to a MCM ship.

Central to this alternative is the idea that the SPUDS vehicle is a fully autonomous/semi autonomous vehicle. It processes MCM/navigational sensor data in real-time to navigate, collaborate with other vehicles, and to search, detect, classify, and identify mines without human

intervention. Real-time mine mission analysis (MMA) is processed on board the vehicle itself. This alternative leaves the option of PMA, in that sensor data is recorded onboard the vehicle to be retrieved at a later time. The primary advantage of Alternative One is the reduced personnel and infrastructure to conduct MCM operations. In this option the Host Platform can control many SPUDS vehicles with a minimum number of people and resources.

Figure 41 depicts the Alternative One concept vehicle. The human has no ability to physically see the vehicle while it is conducting its mission due to the MCM ship being in an OTH location. For this reason, the underwater vehicle has navigational sensors and computer power to understand its location underwater. This is done through navigation computer systems that regulate the vehicle's speed, direction of travel, and accelerations as it guides the vehicle through a MCM operation. The Host Platform assigns patterns, waypoints and tasks to the vehicle, but it is the vehicle's responsibility to negotiate obstacles and determine best routes to accomplish the mission. In order to accomplish this task, the navigation system depends on a number of schemes to keep the vehicle on course and on track. The biggest obstacle to performing navigation is doing it covertly. In order to meet the clandestine requirements, the vehicle must stay submerged for most of its mission. In this concept, communication and navigation aids are provided by establishing an autonomous buoy field.

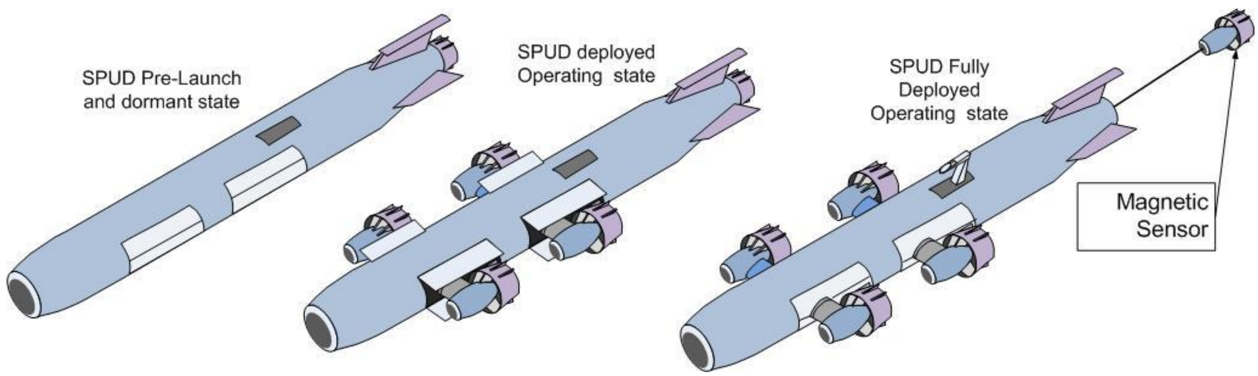

Figure 41. SPUDS Vehicle: Alternative One

This figure depicts the way the magnetic sensor is deployed from the Alternative One SPUDS vehicle.

a. Alternate One: SPUDS Vehicle Concept

The concept for the SPUDS propulsion system, power distribution system, and MCM sensor system remains the same the base MCM Advanced System. However, the components of the navigation system, mission processing system and communication system differ from the other alternatives in redundancy. Figure 42 shows the component diagram of Alternative One by breaking out the components of the system.

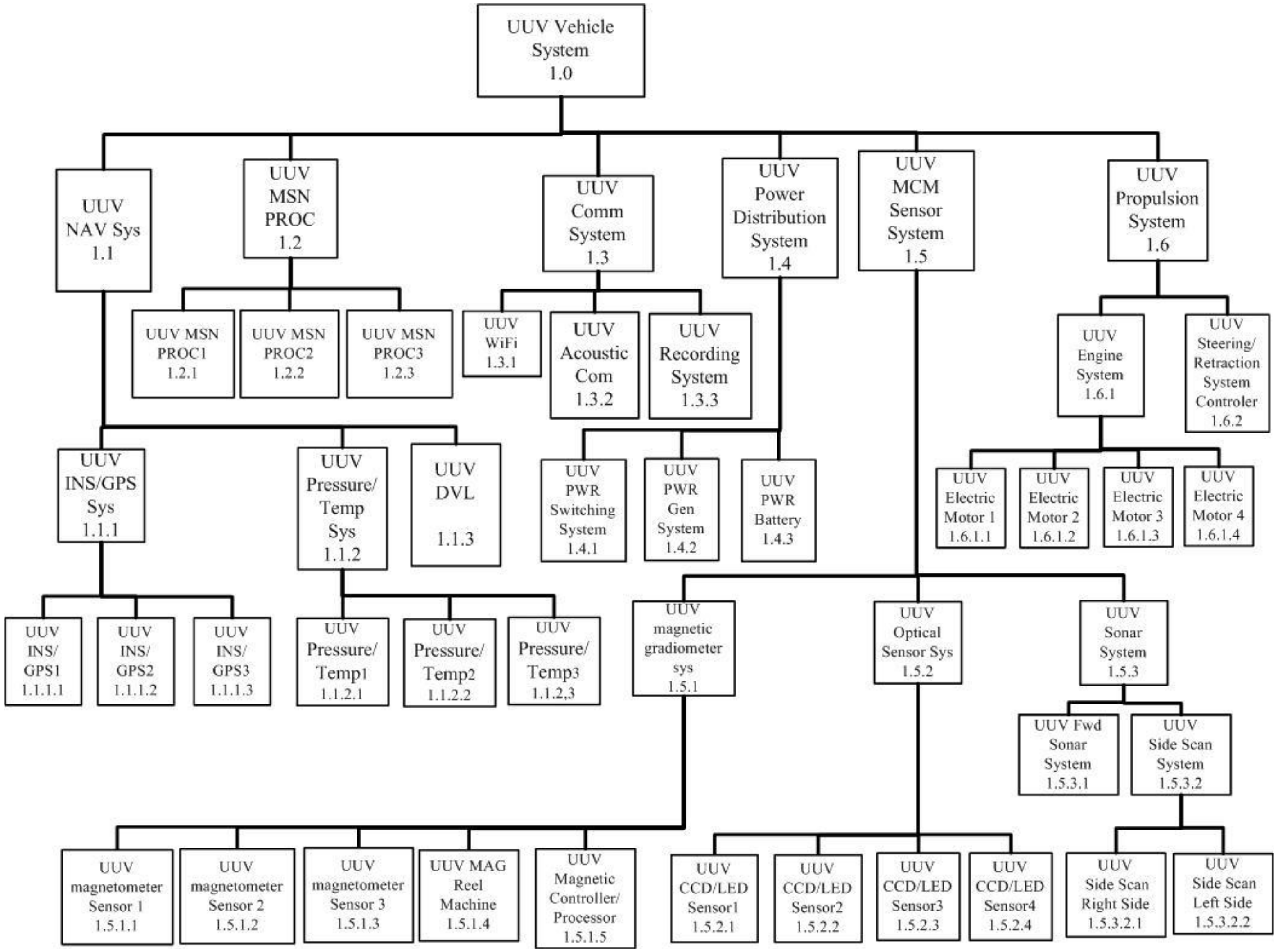

Figure 42. Alternative One - Fully Autonomous SPUDS Component Diagram

This figure depicts the component diagram of Alternative One. The vehicle consists of navigation, mission processing, communication, power, sensor, and propulsion systems.

Alternative One utilizes three independent navigation systems that are weighed against each other to minimize navigation errors. In this system there are 3 independent Inertial Navigation Systems (INS) that provide heading, 3-dimensional velocities, and latitude/longitude position. The use of three independent systems provides the ability to use a voting system for navigation error correction. This gives the ability to correct for one of the systems being incorrect. If there were only two INS systems and they are in disagreement, there is no way to correlate which system is correct. A minimum of three INS systems provides the ability to differentiate which system is out of tolerance and thus provide error correction and reliability. The INS computers interface to three independent mission computers as shown in Figure 43. The mission computers contain the main functionality for computing the navigation solution. In addition to the INS computers, the mission computers interface to a Doppler Velocity Log (DVL) device, and pressure/temperature sensors. The computers compare navigation solutions and create error corrections for the INS systems. Since INS are prone to accumulative error drift for far distance and long time navigation, two different approaches are taken to compensate for errors by creating a synthetic navigation solution.

The first approach utilizes information coming from MCM sonar and DVL and compares this information to a database model of the terrain to create a multi-beam bathymetric system (MBS). This approach was suggested in a study using underwater synthetic navigation with INS, sonar, and a sequential similarity detection algorithm (Zhang, Meng, Zhao, & Shao, 2009). This approach uses a technique to provide error correction to the INS of the UUV by matching the background field coming from the bathymetric data that is provided by the sensor system to a vehicle target location using virtue of matching algorithms. A conceptual processing block diagram of this method is shown in Figure 44.

The second method calculates the range to a known point as shown in Figure 43. In this concept an acoustic/navigation buoy with a GPS receiver is planted in the AO. The SPUDS vehicle queries the buoy and the buoy responds back with an encoded signal containing the buoy's latitude/longitude location. The encoded location of the buoy is based on its position obtained from the buoy's GPS receiver. The time between the SPUDS vehicle querying the buoy and the buoy's response can be used to calculate the distance between the SPUDS vehicle and the buoy. The range can be more accurately calculated with the use of the SPUDS vehicle’s depth pressure transducers and DVL. With the position and range of the buoy being known, the SPUDS vehicle can use the information to correct errors in the INS. This technique was proven to be successful in a simulated experiment and document in an IEEE Journal of Oceanic Engineering in 2007 (Lee, Jun, Kim, Lee, Aoki, & Hyakudome, 2007).

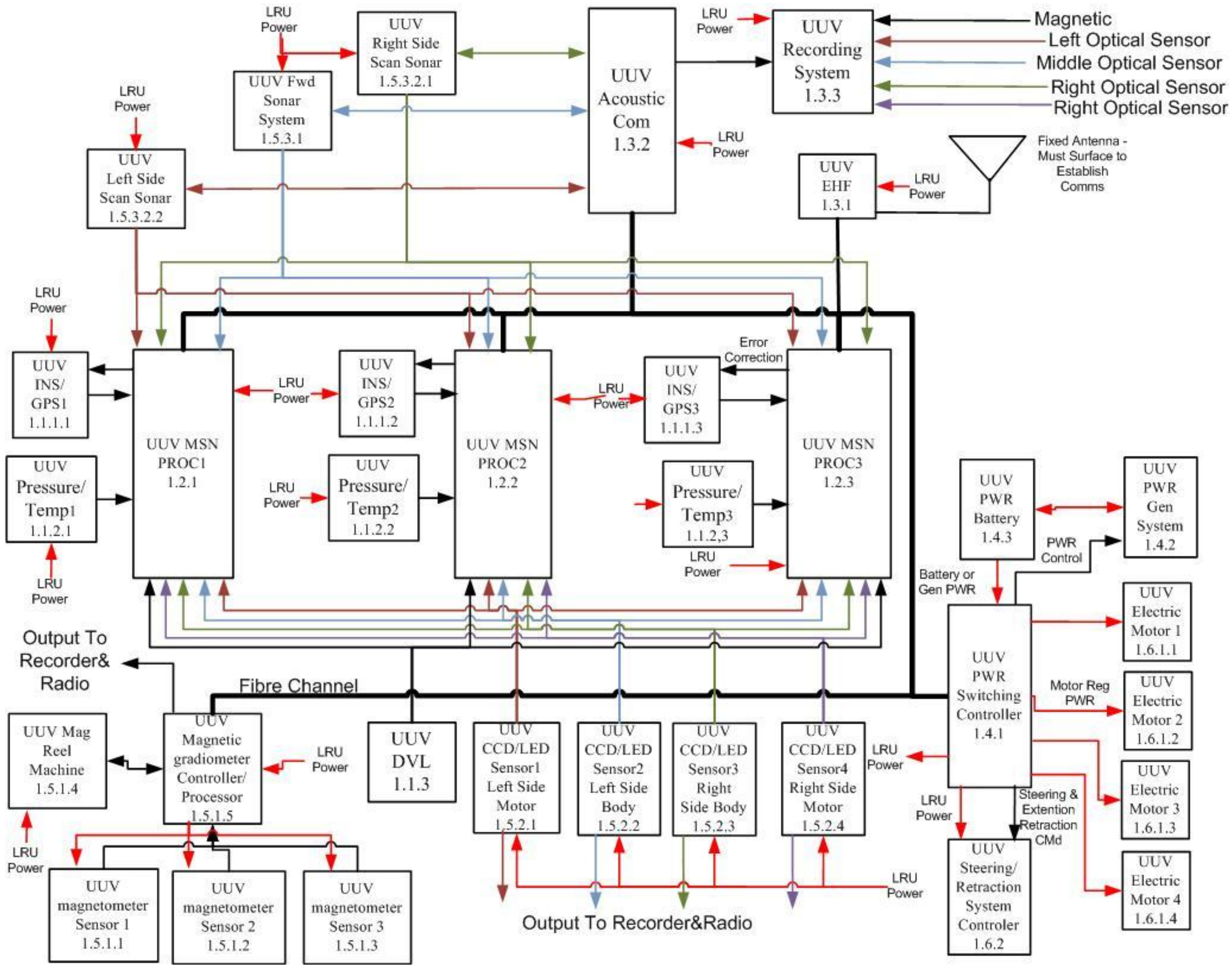

Figure 43. Alternative One Conceptual Schematic Block Diagram of SPUDS

This figure depicts a block diagram model for Alternative One. The figure shows the inputs and outputs to the system components. The different colors of inputs and outputs from the various components help trace power requirements and signals. The red color indicates a power input, while black and other colors show sensor inputs/outputs.

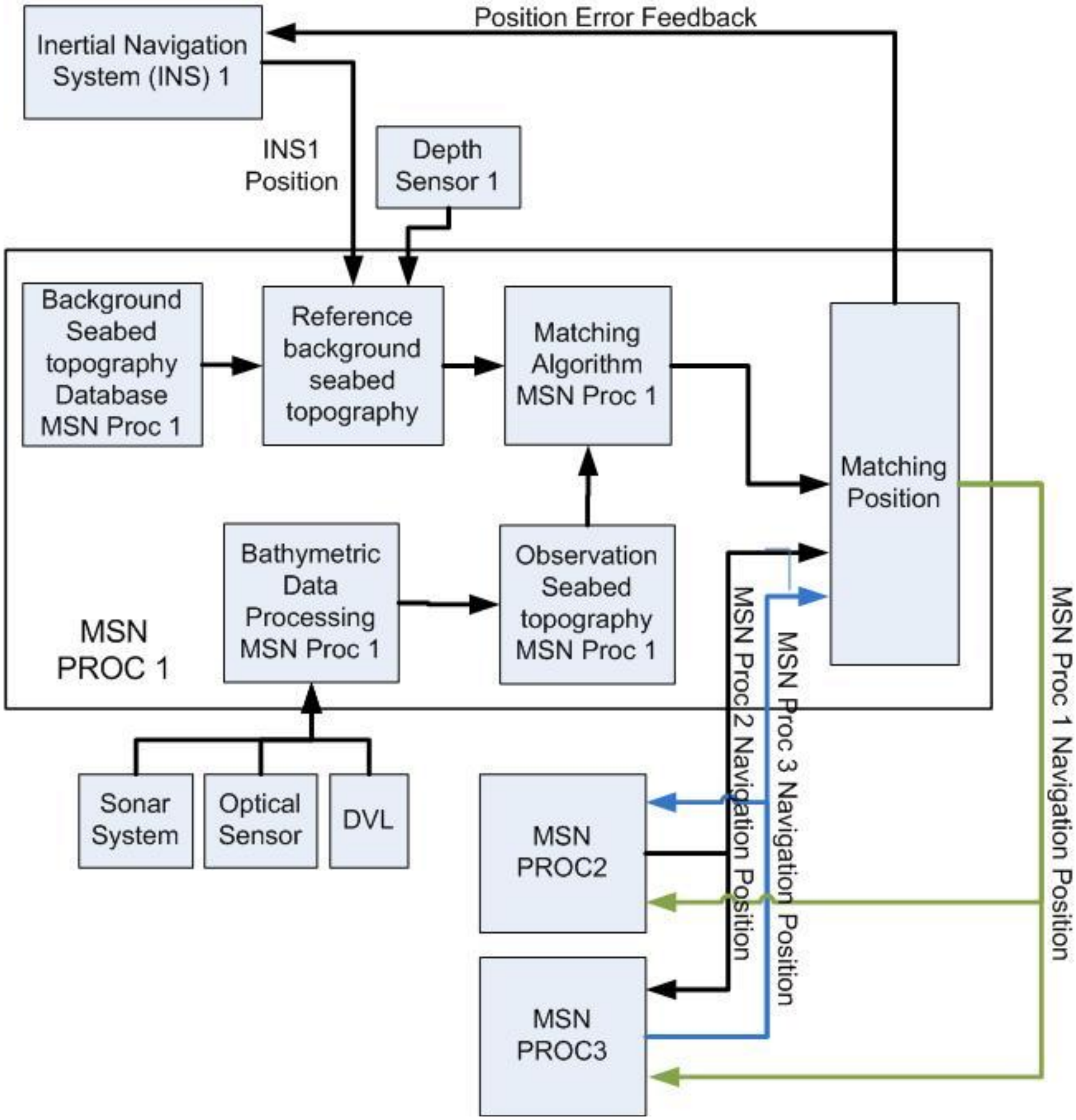

Figure 44. Alternative One INS/Multi Beam Bathymetric Navigation Processing

This figure depicts a conceptual block diagram for comparing the seabed topography with database topography and calculated positions from 3 independent processors to correct INS drift errors (Zhang, Meng, Zhao, & Shao, 2009). The different colors are used to differentiate positional data outputs from the processors. Essentially, the three mission processors are comparing their data for better accuracy.

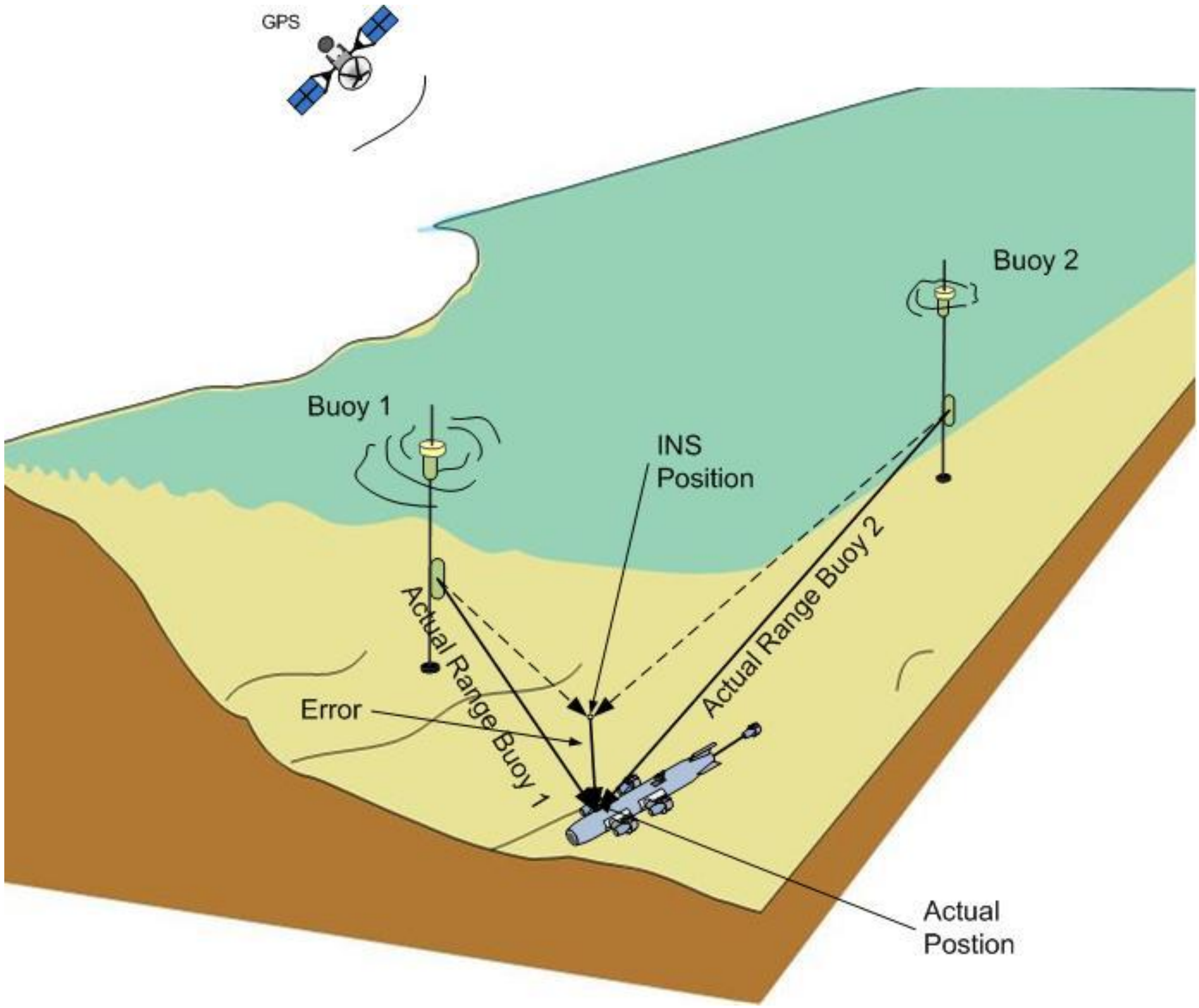

Figure 45. Alternative One Acoustic Navigation Buoy

This figure depicts the concept of correcting INS errors using navigation/communication buoys (Freitag, 2005).

Using both techniques with three independent systems, the SPUDS vehicle should be able to obtain high navigation performance for long periods of time. However, if the systems fail or acquire error, the SPUDS vehicle can surface to obtain a navigation location from its GPS receivers. Once this is done, the SPUDS vehicle can align its INS systems with the coordinate and continue on with the mission. If two of the three navigation systems fail, the SPUDS vehicle can augment its navigation solution with periodically surfacing to get a GPS fix.

In addition to navigation, the MCM sensor systems outputs are interfaced to the three mission processors. The mission processors independently fuse the sensor information and use auto-target recognition algorithms to detect, classify, identify, and locate the mines. Once again the mission processors compare answers to confirm or deny suspected outcomes.

The SPUDS vehicle is able to communicate by radio or acoustically by modulating its sonar. The underwater communications is established with creation of an underwater acoustic communication system. In 2004, the REMUS project very successfully established communications using Frequency-shift-key/ frequency-hopped (FSK/FH) method in VSW/SZ area (Freitag, 2005). The FSK/FH method employed a utility acoustic modem (UAM) operating with a default data rate of 80 bps with overhead error correction that enabled 25 kHz underwater communications with 4 kHz of bandwidth. There is research being conducted that is exploring underwater communications with higher data rates and wider bandwidths. Some experiments have created success in transmitting data rates from 3.7 to 11.6 kbps over distances of 300 to 2500 meters (Goalic, Trubuil, Laot, & Beuzelin, 2010).

However, it is anticipated that these higher data rate are not needed because the amount of data in the form of positional data, mine contacts, mine locations, and mine types is low because the sensor data has already been processed. In other words, with the raw sensor data being already processed and the vehicle guiding itself autonomously with very sporadic communication needs, there is no need for high bandwidth communications. The low bandwidth communications which adapts itself well to underwater communications should prove adequate as demonstrated by the REMUS project. The primary communications are performed acoustically with the radio as backup communication source. SPUDS communicates with the Host Platform through a buoy system detailed later in this section. A SPUDS vehicle is also able to communicate acoustically with other SPUDS vehicles in performing collaborative search efforts through the same buoy system.

b. Alternative One: Host Platform Concept

The Command and Control communication system used for the Host Platform is composed of a Wi-Fi compatible radio, server, recorder/playback system, switch and a video encoder as seen in Figure 46. It should be noted that Wi-Fi is a registered trademark of the Wi-Fi Alliance (Wi-Fi Alliance, 2012) and is being used here in a generic sense of promoting a commercial off the shelf (COTS) solution for communications. Further discussion of this communications concept is found later in this report. The Wi-Fi radio provides the radio link to the SPUDS vehicle.

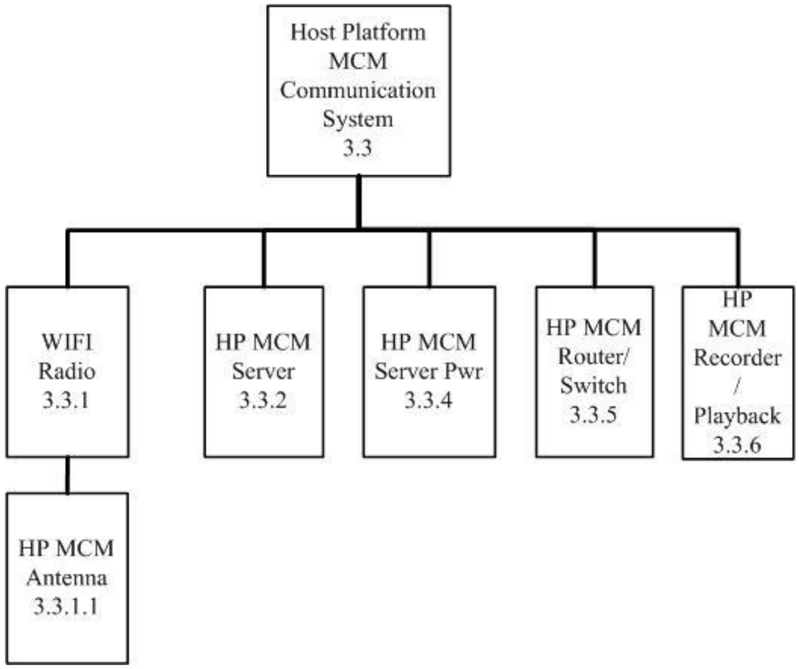

Figure 46. Alternative One Host Platform Communication System Diagram

This figure depicts the components of the host vehicle platform.

Figure 47 depicts that the system only requires two operating stations, one oversight station, and one operating station to control multiple SPUDS vehicles. Since, the vehicles themselves make decisions on routes, mines, and mission accomplishments, the command and control personnel are drastically reduced. However, the human maintains a very high level view of the mission and operations.

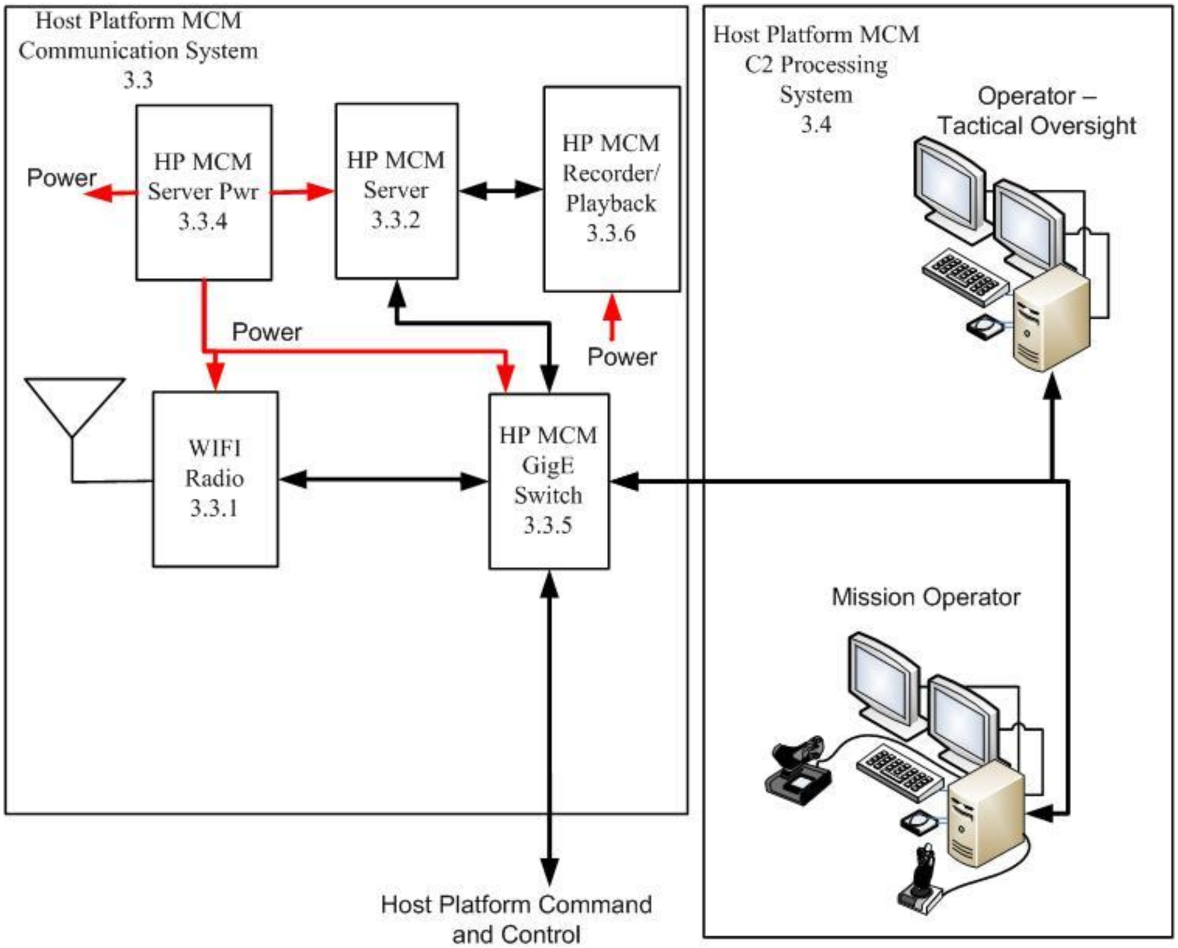

Figure 47. Alternative One Host Platform C2 Schematic Block Diagram

This figure depicts the components of the host vehicle platform. Red lines indicate power inputs/outputs from the different components, while black lines indicate signal input/output.

Figure 48 depicts the Host Platform Command and Control Processing System for Alternative One. Communication between the Host Platform and vehicles is very sporadic. The host queries the vehicle(s) for location and status. The vehicle responds with location, vehicle health status, mines detected, and mine locations when queried by the Host Platform. Besides querying the vehicle for status, mission operators can give the vehicle(s) high level mission changes by reprogramming routes, search patterns, and waypoints. Mission operators have the ability to take over guidance of a selected vehicle for short amounts of time. Direct control requires a continuous transmission which would use up the bandwidth of the buoy network for communications. Therefore, direct control should be limited to times when the vehicle is severely degraded, for example, steering a disabled vehicle to a pick up point.

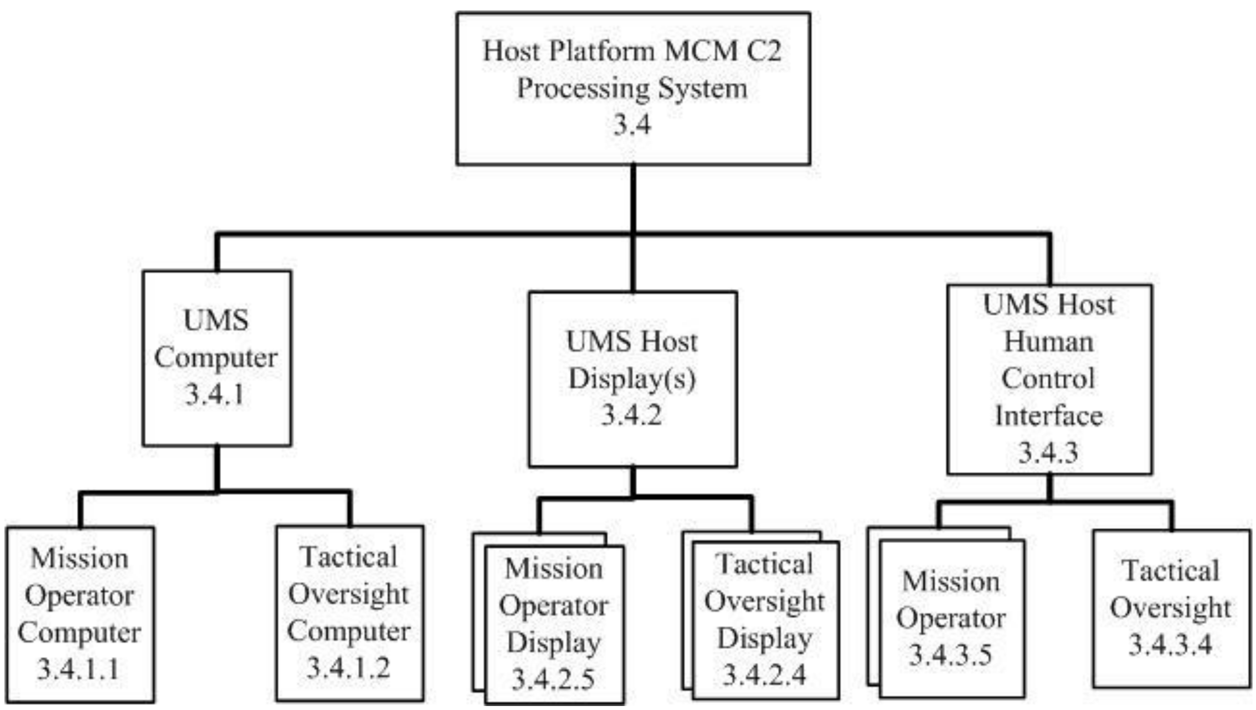

Figure 48. Alternative One Host Platform C2 Processing Component Diagram

This figure depicts the components of the host vehicle platform MCM Command & Control Processing System.

The MCM server stores and retrieves mission data for the MCM system. The MCM switch routes updated tactical information to operating stations and the ship C2. The tactical oversight position provides overall supervision of the MCM C2 system. This position plans routes, neutralization strategies, and vehicle missions based on analysis of the incoming data. The tactical oversight overall responsibility is to develop the tactical map of the AO and communicate routes and mine field locations to the ship's C2. The ship’s C2 is responsible for

passing this information onto the amphibious force. However, the ships net-centric capabilities give the amphibious force the ability to query the overall MCM status without human intervention.

The fully autonomous features presented in Alternative One provide the capability to respond to higher order of directions from human operators. It creates a situation in which the MCM operation can operate with an autonomous net-centric capability. This alternative removes the humans from the control loop and puts them on-loop for making tactical decisions. It allows the MCM system to operate multiple MCM vehicles with the least amount of infrastructure in the form of ships and personnel.

c. Alternative One: OTH Communications

Alternative One's communication system relies on the deployment of low cost, autonomously operating communication/navigation buoys. This concept calls for the creation of two different buoys to enable OTH communications between the MCM control ship and the vehicles as shown in Figure 49.

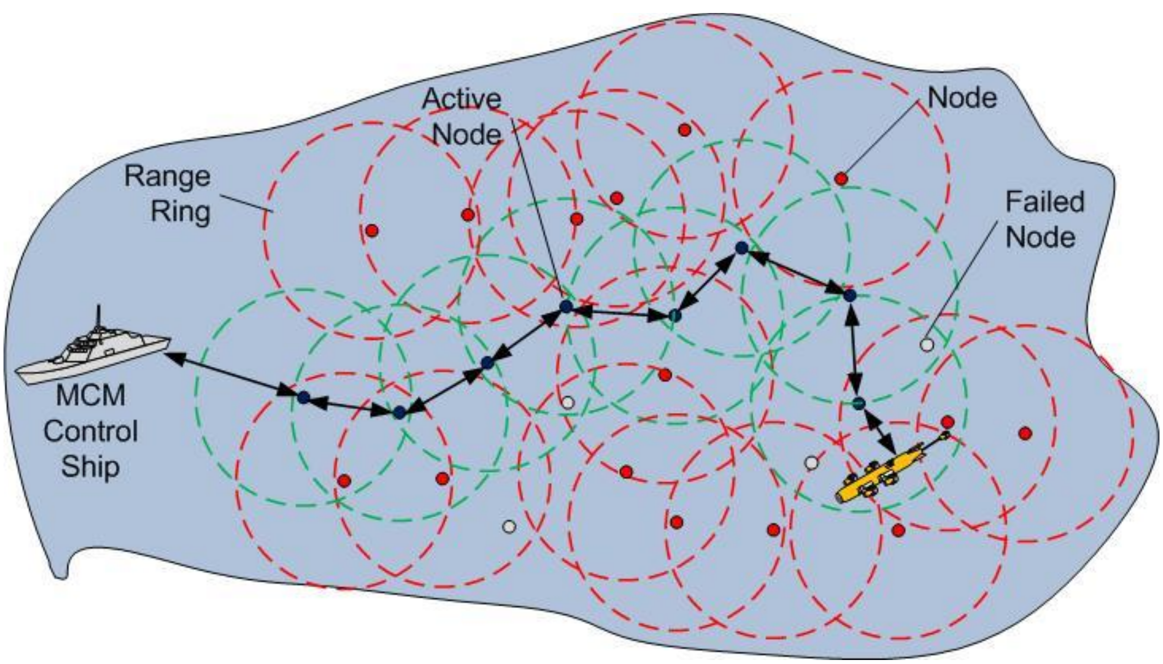

Figure 49. MCM communication path

This figure depicts the communication concept of routing a signal through buoy network field.

Figure 50 depicts the vehicle-to-vehicle communications. In this concept, one buoy type would serve strictly as an RF communication node, and the other as an RF/Acoustic communication/navigation node. There are two different physical communication layers with this concept. One physical layer involves communicating via an RF wireless data link and the other is by an underwater method using a FSK/FH.

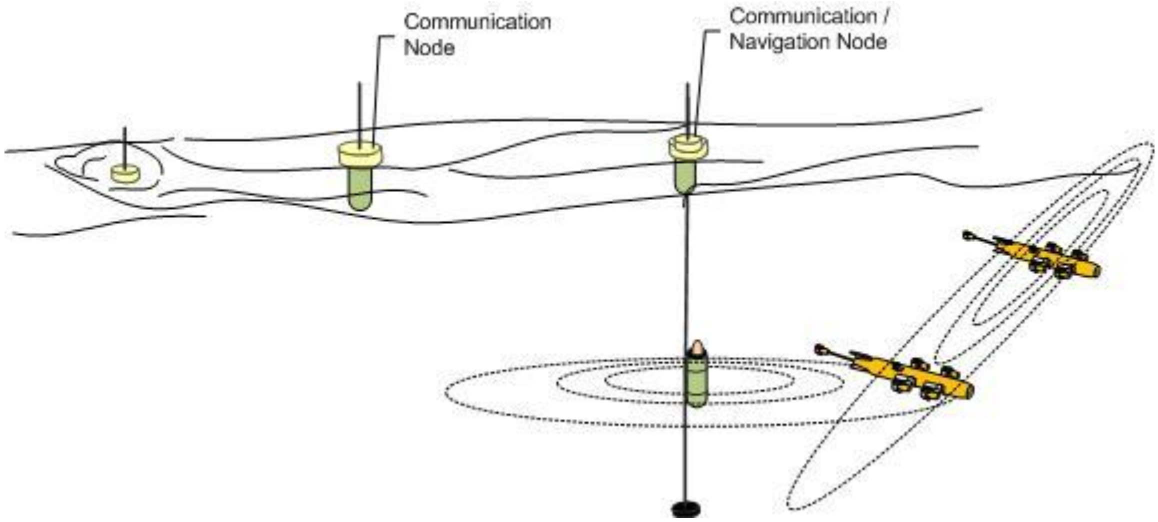

Figure 50. Communication/Navigation Buoy

This figure depicts the communication concept for communication and communication/navigation buoys working with SPUDS vehicle.

The communication buoys make up nodes that create a wireless integrated communications network with an underwater acoustic network. With advancements in low-power circuits and networking technologies, the RF network nodes can last up to three years with less than a 1% duty cycle working mode on 2 AA batteries (Yu, Prasanna, & Krishnamachari). However, this type of time frame is not needed for the MCM operation; but it shows the area of interest (AI) can be seeded with these types of buoys long before they are needed. These buoys could be seeded covertly during times of low visibility in the AI and remain dormant until needed. A number of means using the existing Navy infrastructure for dropping buoys such as by air as shown in Figure 51. Dropped buoys are not recovered, but are designed to sink and self-destruct critical circuitry upon command, or when battery sources run low.

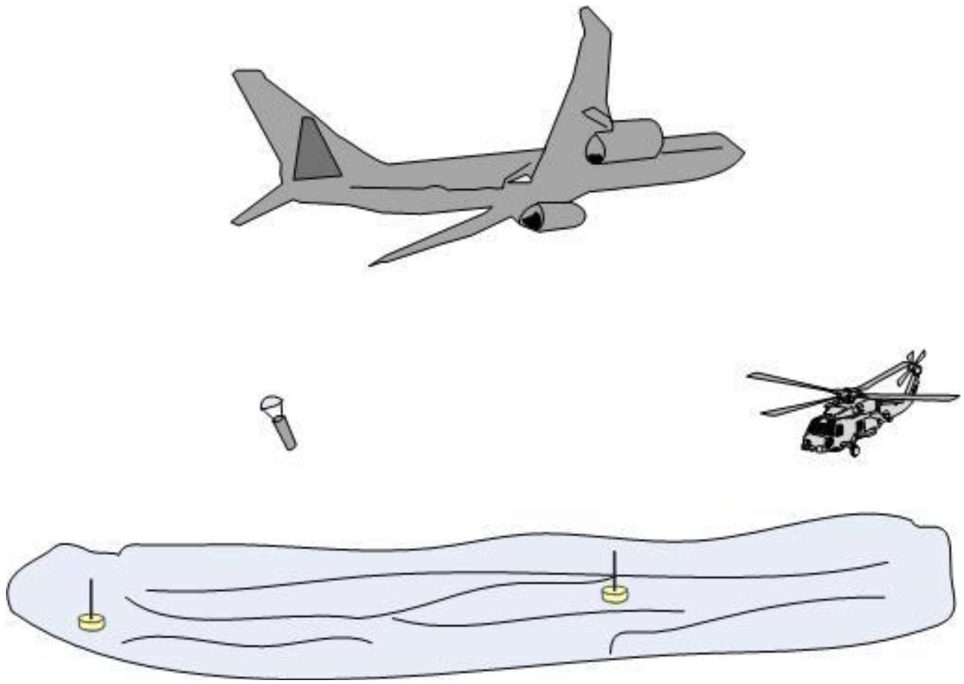

Figure 51. Air Drop buoys

This figure depicts different Host Platforms that could seed the buoy network field.

The communication nodes are responsible for self-organizing an appropriate network infrastructure with multi-hop connection between sensor nodes. The network is self-healing, dynamically reconfigurable, with a random topology. The basic idea is that individual wireless buoy nodes are limited, but the aggregate power of entire network is sufficient for all types of communications. The MCM Host Platform can retrieve information of interest by injecting queries and gathering results from the network.

Each communication node has an individual IP address making it unique in the network. The communication nodes maintain location and positioning information obtained from GPS to enable localization techniques. The communication nodes use the localization techniques to optimally transmit data between the MCM control ship and MCM vehicle as shown in Figure 49. This requires the buoy to not only be aware of its status, but the statuses of the buoys around it. As a result, the communication node is able to route data through the network until it arrives at its intended sink, which is the MCM control ship or MCM vehicle.

Note that not all communication nodes will transmit data, thus allowing for a lower duty cycle on the sensor nodes, enabling power conservation. When bandwidth is needed, data is aggregated across the network to expand the capabilities of communication. It is beyond the

scope of this project to identify the optimal protocol for this network. However, it is suggested that ZigBee IEEE 802.15.4 protocol should be analyzed further for possible implementation because this protocol design supports a low data rate, low power consumption, low cost, design that targets automation and remote applications. ZigBee IEEE 802.15.4's drawback is its range limitations, typically between 10 and 75 meters. Data protocols such as IEEE 802.11 with the right kind of transmitter/receivers can handle ranges of up to 100m. For ranges of up to 2Km, standards like GSM, IS-136, and IS-95 should be studied for applicability (Ergen, 2004).

This report recommends using a Wi-Fi compatible radio for Alternate One. As previously stated Wi-Fi is a trademark name for the Wi-Fi Alliances, which is a non-profit organization, whose goal is the adoption of high-speed wireless local area networking (Wi-Fi Alliance, 2012). It is used here in the generic sense to create a wireless system which uses a radio that transmits and receives in the 2.4 GHz and 5 GHz frequency bands. The bandwidth of these radios systems are 20 MHz. However, using IEEE 802.11n which introduces the use of Multiple Input Multiple Output (MIMO) features, the bandwidth can be increased to 40 MHz with data rates up to 600 Mbits/s by the utilization of channel bonding, spatial division multiplexing and space time blocking coding (Friedrich, Frohn, Grrbner, & Lindermann, 2011). It is beyond the scope of this report to examine the pros and cons of using or militarizing a commercially-developed standard for wireless communications. However, it should be pointed out that the commercial world is driving the development of creating hardware and software protocols with built-in security and error protection. With the proliferation of this technology the economic pressures drives down the cost, size, and increases the availability of this technology. These COTS items can easily be re-packaged into a low-cost military application. This technology is readily available to create a multi-hop communication wireless network.

It can be argued that wide bandwidth and high data rates are overkill to control one to several autonomous vehicles. This is especially true when the underwater communication needs calls low bandwidth communications. However, a mesh buoy network system can serve more purposes than just providing underwater communications to MCM vehicles. It can also be used for an Anti-Submarine Sensors Network that can alert an advance amphibious force to the presence of submarines near buoy locations. US doctrine states that the enemy will employ submarines in creating an anti-landing defense (Joint Publication 3-02, 2009). Therefore, the bandwidth and high data rate requirements can be leveraged to utilize the buoy network for other tasking such as to supplement communication needs and provide advanced reconnaissance information. This is beyond the scope of this report and it is recommended for further study.

The buoy system is advantageous in that it is inherently clandestine due to its low visual and radar traceability. Additionally, with the sporadic transmission times, when the MCM Host Platform must communicate with the vehicle, the system maintains a relatively small electromagnetic signature. The buoys also have the advantage that they allow for larger amounts of data to be transmitted across the network. Since the buoys are low cost, the MCM operation can create a deceptive operation by seeding buoys in an area that is not intended for the amphibious landing. Thus it can be used to create an illusion of an impending amphibious operation in a location that is not intended to be attacked

d. Alternative One: Equipment & Personnel

It takes two people to operate Alternative One in the field; however, this analysis has not addressed the number of people needed to support the maintenance of the system. We estimate that the number maintenance personnel needed will be at minimum three persons, which includes maintenance of SPUDS power and propulsion systems, maintenance of mission LRU's, and maintenance of Host Platform computer systems. However, a level of repair analysis (LORA) and maintenance plan will be needed to accurately estimate the number of personnel needed to maintain and repair the system. This is beyond the scope of this report, but a rough estimate of 3 people is provided for cost estimating purposes. It should be noted that Alternative One allows the operators to control more than one SPUDS without increasing the manpower or Host Platform C2 equipment requirements. Table 14 is a summary of the equipment needed to deploy one SPUDS system.

Table 14. Alternative One Equipment List Summary

This table summarizes the Alternative One components described in this section. The number of buoys for the operation is dependent on distance and location of the MCM Host Platform from the AO. This will have to be calculated for each mission.

Platform	Equipment	Sub Component	Number
SPUDS Vehicle	INS/GPS	N/A	3
	Depth Pressure Sensor	N/A	3
	Temperature Sensor	N/A	3
	DVL	N/A	1
	Wifi Radio	N/A	1
	Wifi Radio Antenna	N/A	1
	Acoustic Communication Interface Box	N/A	1
	Recording System	N/A	1
	Power Switching System	N/A	1
	Power Generation System	N/A	1
	Battery System	N/A	1
	Magnetic Gradiometer	Magnetic Controller Processor	1
		Magnetic Sensor	3
		Reeling Machine	1
	Optical Sensor	CCD/LED Sensor	4
	Sonar System	Forward Looking Sonar Transducer	1
		Left Side Scan Sonar	1
		Right Side Scan Sonar	1
	Engine Controller	N/A	1
	Electric Engine	N/A	4
	Steering Retraction System	N/A	1
Host Platform	WiFi Radio	N/A	1
	WiFi Radio Antenna	N/A	1
	Server	N/A	1
	Server Power Supply	N/A	1
	Router/Switch	N/A	1
	Recorder/Playback	N/A	1
	Operator Computers		2
	Displays		4
	Keyboards		2
	Trackball		2
	Throttle Control		1
	Joystick Control		1
OTH Communication	Communication Buoy	N/A	See Note
	Communication/Navigation Buoy	N/A	See Note

e. Alternative One: Component Mapping to Functions & Requirements

Table 50 and Table 51 in Appendix E contain the component mapping of Alternative One to the associated functions and requirements previously defined in this report to verify that the system has been properly designed. It should be noted that the generic mapping was completed in Table 9 and Table 10 of this report.

2. Alternative Two

Alternative Two revolves around the concept that the MCM ship (or Host Platform) operates the SPUDS vehicle via a radio signal. Central to this alternative is the idea that sensor outputs are transmitted to the human operators in real-time aboard the MCM ship. Real-time mine mission analysis (MMA) can be done aboard the ship while the mine vehicle is in the search area. This alternative does leave the option of PMA in that sensor data is recorded both on board the MCM ship, and inside the SPUDS, but it is advantageous to reducing the detect to engage timeframe by performing real-time MMA. The MCM ship will be a littoral combat ship and Alternative Two provides the MCM mission module that is installed on the ship. Figure 52 depicts the Alternative Two conceptual operations.

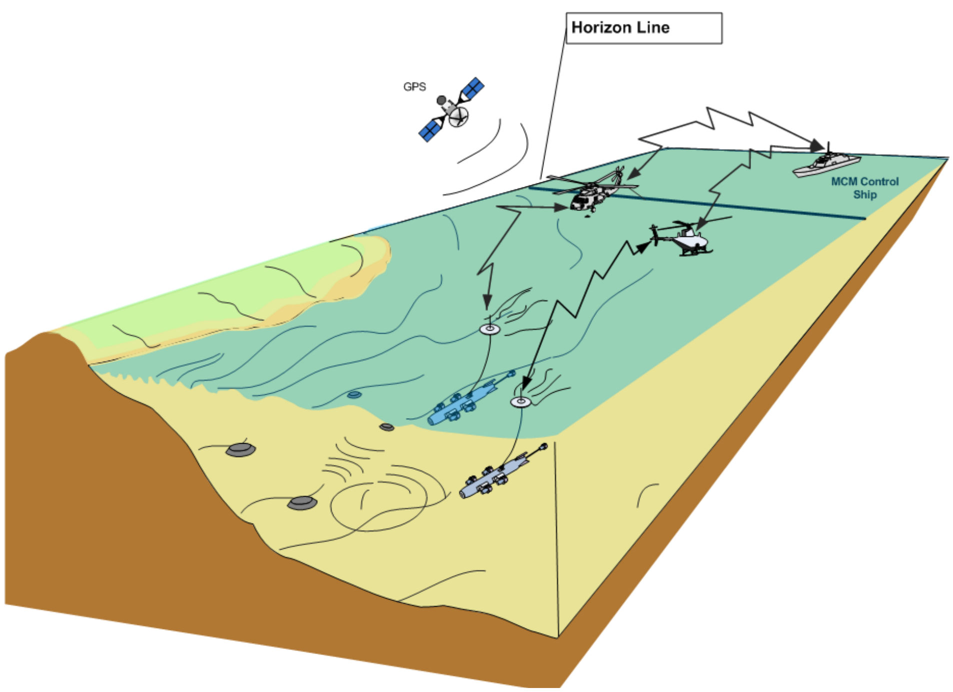

Figure 52. Alternative Two: Operational Concept

This figure depicts the operational concept of Alternative Two. The underwater vehicle relays search information back to a MCM ship using a surface-tethered radio link. The data is first transmitted to an air platform, and then relayed back to a MCM ship.

For Alternative Two, the human has no ability to physically see the vehicle due to the MCM ship being located OTH. For this reason, the underwater vehicle has navigational sensors and computer power to understand its location underwater. Navigation is performed through Inertial Navigation Systems (INS) and GPS computer systems that relay the unit's speed, direction, accelerations, and global location (GPS). Due to signal reception limitations when using GPS below the water, it is required that the SPUDS vehicle use an antenna that is on the surface by way of a wired tether. As a backup, the INS is used to deliver other navigational data when the GPS antenna has trouble connecting to a satellite.

The surface tether also serves the important function of transmitting sensor and location data back to the Host Platform in the form of radio signals. Due to the longer distance that is imposed by an OTH operation, the radio signals first must be transmitted to an air platform in the area. This is done by using a helicopter or UAV. From the air platform, the data is then relayed back to the Host Platform as shown in Figure 53.

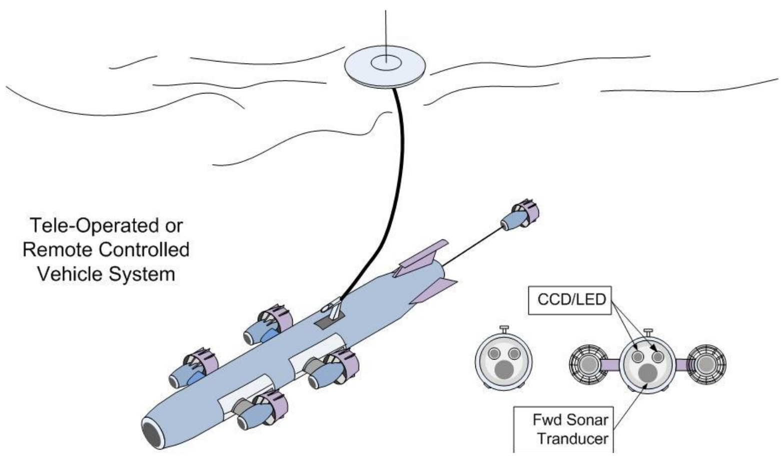

Figure 53. SPUDS Vehicle Tethered Communications

This figure depicts the way the tethered antenna will be used from the underwater vehicle. This figure also shows the front view of the SPUDS with the embedded sensors.

In Alternative Two, the SPUDS vehicle utilizes a communication system composed of Tactical Common Data Link (TCDL) system. The OTH Communication system component is accomplished using existing Navy assets such as an MH-60 or Fire-Scout UAV to provide the data-link communications. The communication system is dually redundant to increase reliability of communications.

The sensor suite of the system is composed of magnetic gradiometers that have three magnetometer sensors, two optical sensors, and a sonar system composed of a forward-looking and two side scan sonar systems.

The SPUDS vehicle's onboard processor provides a navigation solution and processes steering and propulsion commands. However, the processor has a limited ability to process MCM sensor information. This limited ability allows the processor to detect the presence of an undersea object, but does not have the ability to classify or identify a mine. This functionality is assigned to the MCM Host Platform.

This alternative carries the advantage that it is possible to complete the MCM operations in a clandestine manner. Besides the possibility of detecting an aerial platform providing the communication network, there are no surface platforms or people that would be visible in the search area. However, this alternative does carry a higher operational burden in the form of costs and required support aboard the MCM ship. There has to be at least one operator that is controlling the SPUDS, while at least one analyst reviews the sensor and video data to determine if there are mines in the search area.

a. Alternative Two: SPUDS Vehicle

Figure 54 depicts the components of Alternative Two. The Alternative Two SPUDS vehicle consists of navigation, mission processing, communication, power, sensor, and propulsion component systems.

Figure 55 is a block diagram showing how Alternative Two functions as a tele-operated system. As shown in the figure, sensor data from the optical, magnetic, and side scan sonars are fed into the UUVs mission professor. The information is processed in the onboard computer allowing the system to understand and detect possible mine-like objects in the search area. These possible mines that are found are transmitted back to the MCM ship's operators using the UUV's tethered antenna.

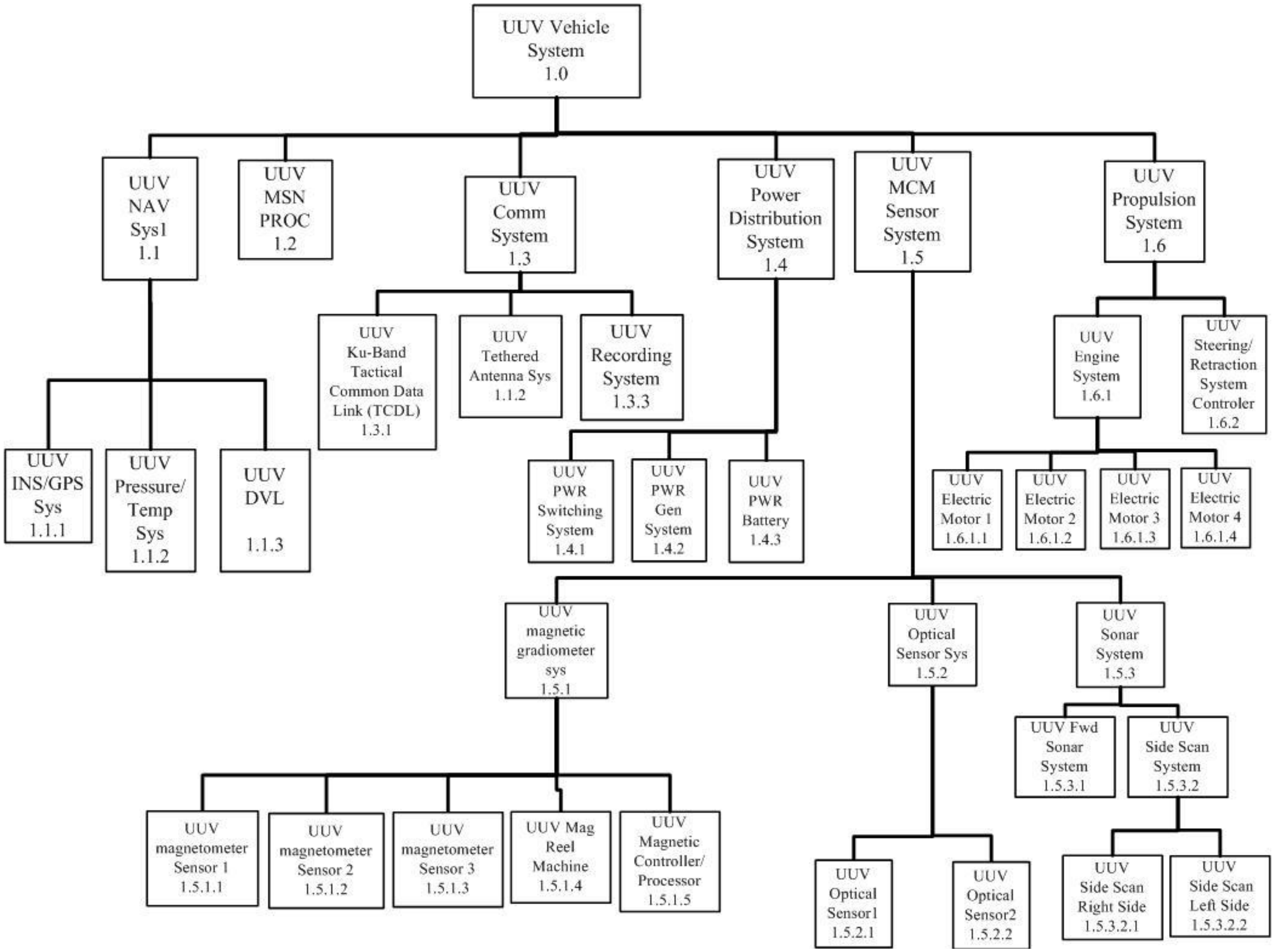

Figure 54. Alternative Two - Tele-Operated SPUDS Component Diagram

This figure depicts the component diagram of Alternative Two. The vehicle consists of navigation, mission processing, communication, power, sensor, and propulsion systems.

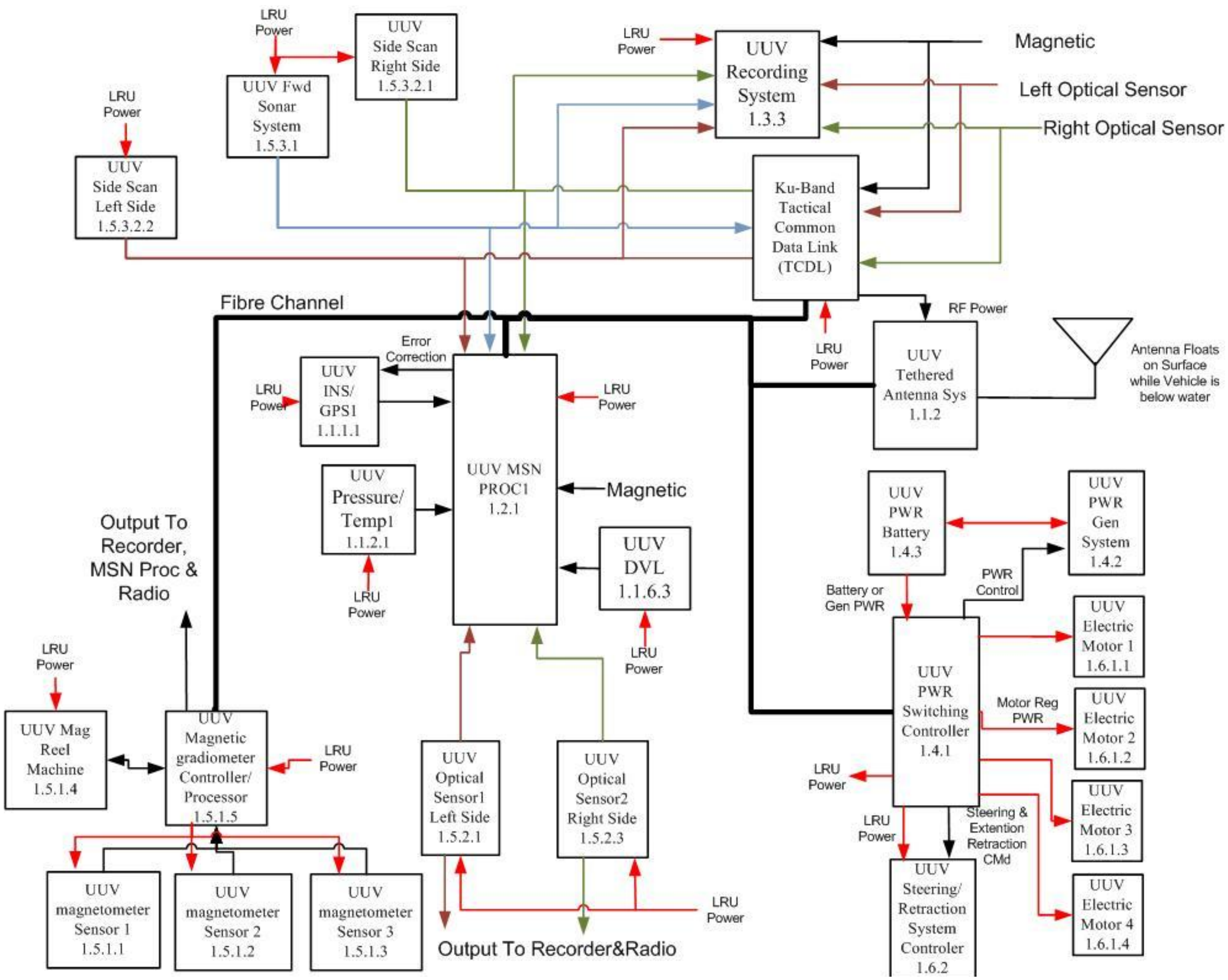

Figure 55. Alternative Two Conceptual Schematic Block Diagram of SPUDS

This figure depicts a block diagram model for Alternative Two. The figure shows the inputs and outputs to the system component. The different colors of inputs and outputs from the various components help trace power requirements and signals. The red color indicates a power input, while black and other colors show sensor inputs/outputs.

b. Alternative Two: Host Platform

Figure 56, Figure 57, and Figure 58 depict the C2 and communication system of Alternative Two that is part of the MCM mission module on the Host Platform. The communication system is composed of a Tactical Common Data Link (TCDL), server, recorder, switch and a video encoder.

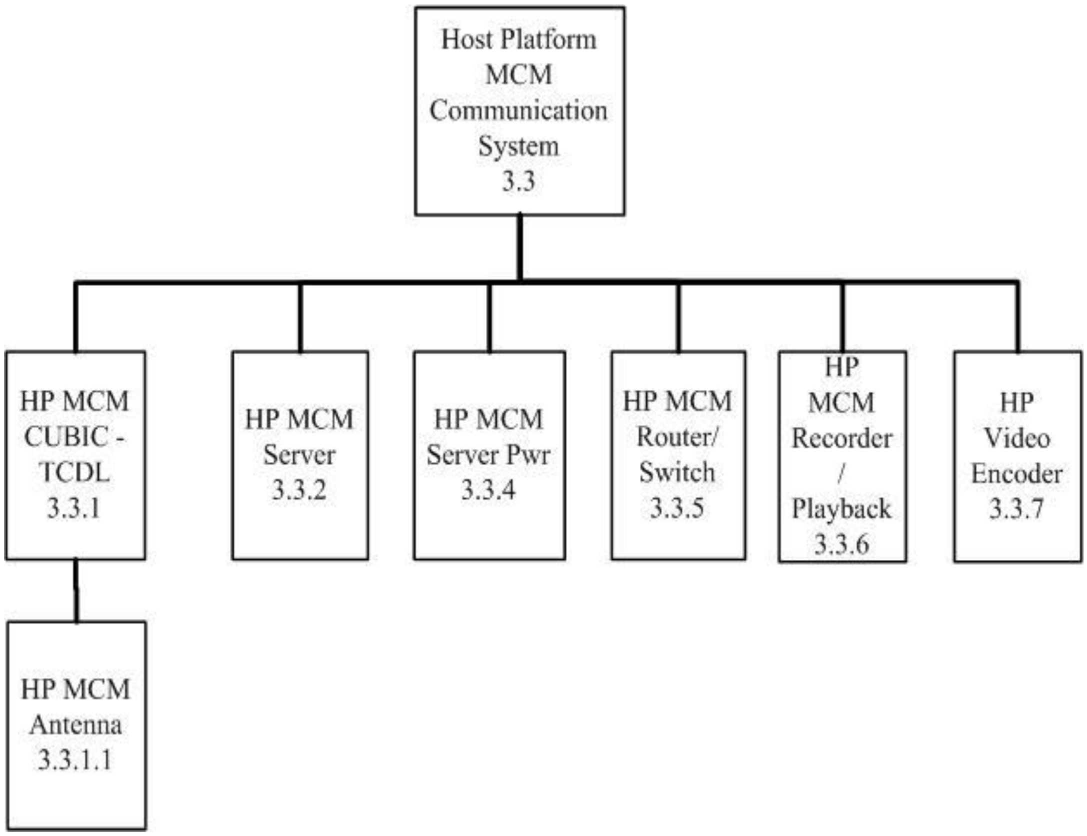

Figure 56. Host Platform Communication System Component Diagram

This figure depicts the components of the host vehicle platform.

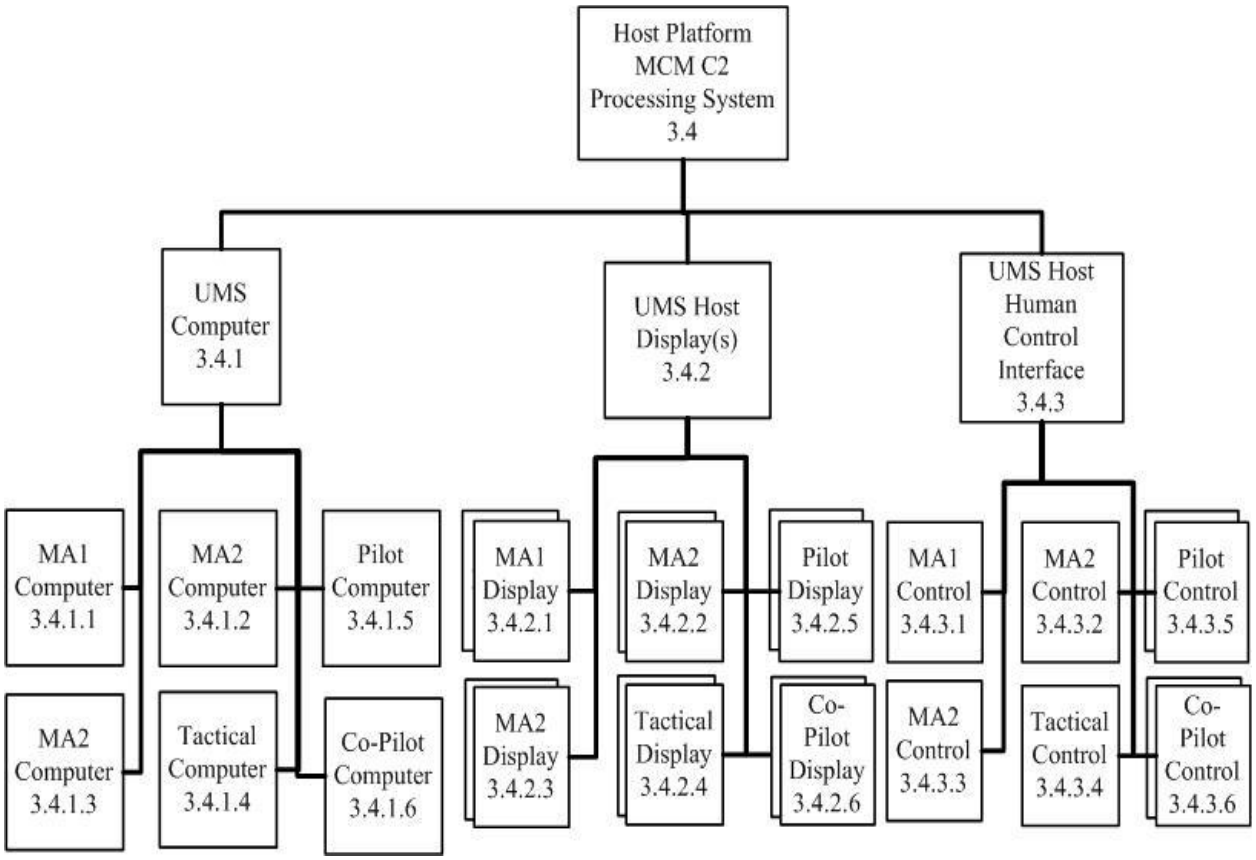

Figure 57. Host Platform C2 Processing Component Diagram

This figure depicts the components of the host vehicle platform MCM Command & Control Processing System. For the purpose of this report "MA" refers to a mission analyst.

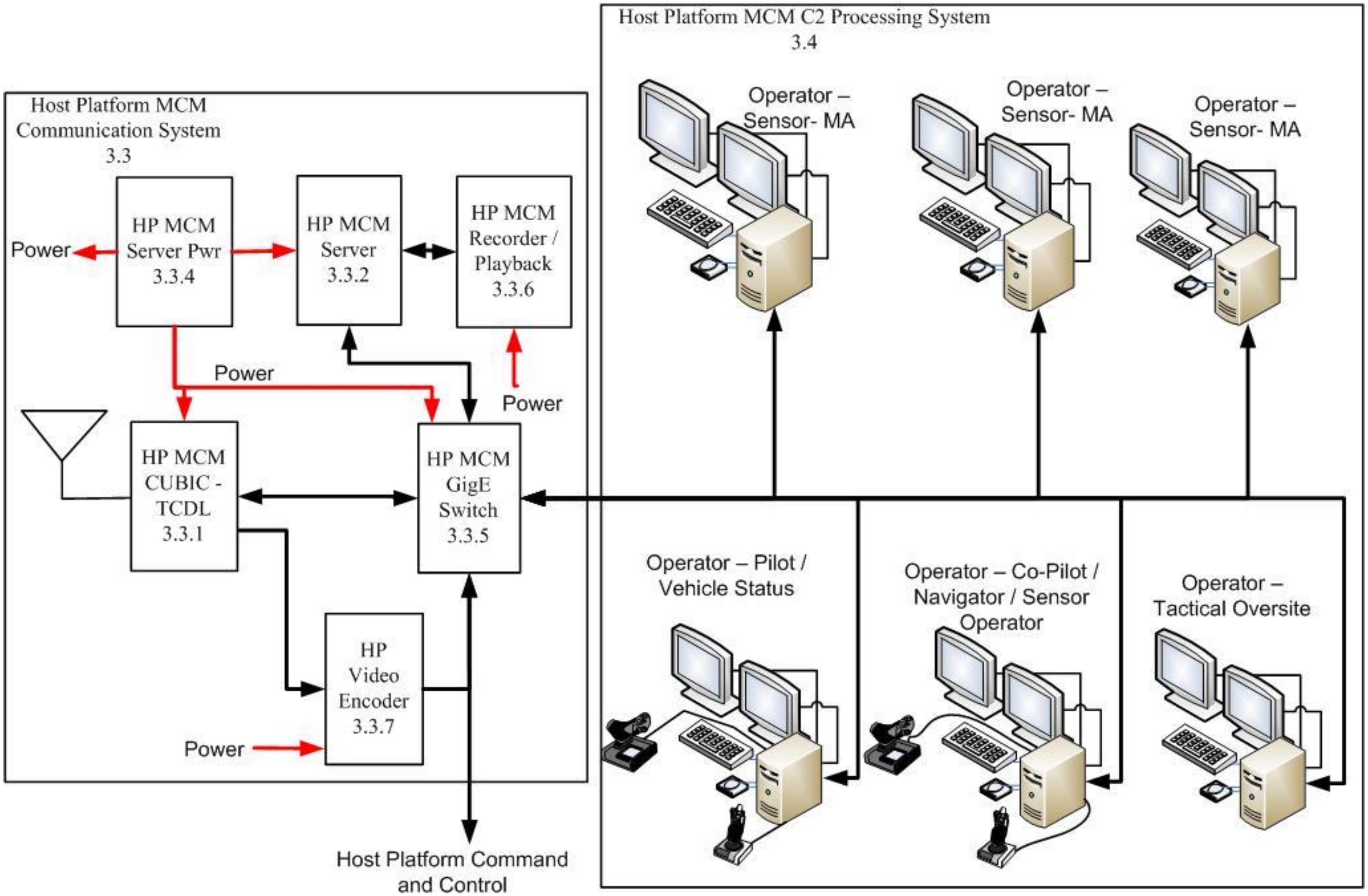

Figure 58. Host Platform C2 Schematic Block Diagram

This figure depicts the components of the host vehicle platform.

The TCDL component of Alternative Two provides the radio link with the SPUDS vehicle. The server stores and retrieves mission data for the MCM system. The switch provides routing of information, and the video encoder encodes the analog video so that it is stored or routed to the operating stations.

The system requires three mission analysts (MAs) to perform real time analysis of sensor data coming from the SPUDS vehicle. The other stations include a pilot, co-pilot, and tactical oversight positions as depicted in Figure 58.

The pilot's main focus is guiding or steering the SPUDS vehicle and maintaining situational awareness of the vehicle's status. The co-pilot is the backup for guiding and steering the vehicle. However, the co-pilot’s main functions are to monitor and provide navigational guidance and monitor and control sensor inputs. The Tactical Oversight position provides overall supervision of the MCM C2 system. This person determines routes, neutralization plans, and vehicle missions based on analysis of data from the MA positions. From there, the operator develops the tactical map of the AO and communicates routes and mine field locations to the ship's command and control, which is then passed on to the amphibious force.

The tele-operated features present in Alternative Two allow the system to be able to follow a higher order of directions input by human operators than that of a remotely piloted UUV. The human operators have the option to input way points and movement directions, and allow the vehicle to carry these out these orders independently using onboard sensors, navigation, and processing capabilities.

The Alternative Two SPUDS is very limited in its onboard decision making and processing power. The UUV does not have the ability to direct other UUVs, or create its own search operations without input from human operators. This alternative relies on a separate neutralization platform to carry out neutralization operations. The neutralization can be coordinated on the Host Platform.

c. Alternative Two: Equipment & Personnel Summary

It will take four to six people to operate Alternative Two; however, this does not include the number of people needed to support maintenance of the system. It is estimated that three maintenance personnel will be needed to provide maintenance of the SPUDS power and propulsion system, mission LRU's, and the Host Platform computer systems. It should be noted that Alternative Two could control up to two SPUDS vehicles without increasing the manpower or Host Platform C2 equipment requirements. However, the OTH communication link will need to be further assessed to verify that it could support more than two vehicles. Adding an additional vehicle may slow down the mission analysis unless the Host Platform includes auto

target recognition routines to assist with the analysis. Table 15 is a summary of the equipment needed to deploy one SPUDS system in the Alternative Two configuration.

Table 15. Alternative Two Equipment List Summary

This table summarizes the Alternative Two components described in this section.

Platform	Equipment	Sub Component	Number
SPUDS Vehicle	INS/GPS	N/A	1
	Depth Pressure Sensor	N/A	1
	Temperature Sensor	N/A	1
	DVL	N/A	1
	TCDL	N/A	1
	TCDL Tether Antenna Sys	N/A	1
	Recording System	N/A	1
	Power Switching System	N/A	1
	Power Generation System	N/A	1
	Battery System	N/A	1
	Magnetic Gradiometer	Magnetic Controller Processor	1
		Magnetic Sensor	3
		Reeling Machine	1
	Optical Sensor	CCD/LED Sensor	2
	Sonar System	Forward Looking Sonar Transducer	1
		Left Side Scan Sonar	1
		Right Side Scan Sonar	1
	Engine Controller	N/A	1
	Electric Engine	N/A	4
	Steering Retraction System	N/A	1
Host Platform	TCDL	N/A	1
	TCDL Tether Antenna Sys	N/A	1
	Server	N/A	1
	Server Power Supply	N/A	1
	Router/Switch	N/A	1
	Recorder/Playback	N/A	1
	Video Encoder	N/A	1
	Operator Computers		6
	Displays		12
	Keyboards		6
	Trackball		6
	Throttle Control		2
	Joystick Control		2
OTH Communication	Existing Navy Assets	MH-60 Date link	As Rqd
		Fire-Scout - UAV	As Rqd

d. Alternative Two: Component Mapping to Functions & Requirements

Table 52 and Table 53 of Appendix E contain the component mapping of Alternative Two to the associated functions and requirements previously defined in this report to verify that the system has been properly designed. It should be noted that the generic mapping was completed in Table 9 and Table 10 of this report.

3. **Alternative Three**

Alternative Three revolves around the concept that the underwater vehicle (SPUDS) is operated remotely by personnel locally within sight of SPUDS. This requires a small team of operators (or local operators) performing the function of transiting SPUDS to the AO by a small rigid inflatable boat as seen in Figure 59. The boat is equipped with the Navy Shipboard Single-Channel Ground and Airborne Radio Systems (SINCGARSs) or a Joint Tactical Radio System (JRTS) which communicates to the MCM platform through a communication relay on an existing Navy airborne platform such as a MH-60 or Fire-Scout Unmanned Aerial Vehicle. In this alternative, there is no real-time mine mission analysis (MMA). The MMA must be done aboard the ship after the SPUDS vehicle conducts its search and the data is retrieved from the vehicle.

Figure 59 depicts the local AO support team needed for Alternative Three. While the MCM ship is in an OTH location, the local operator is responsible to relay information back to the ship.

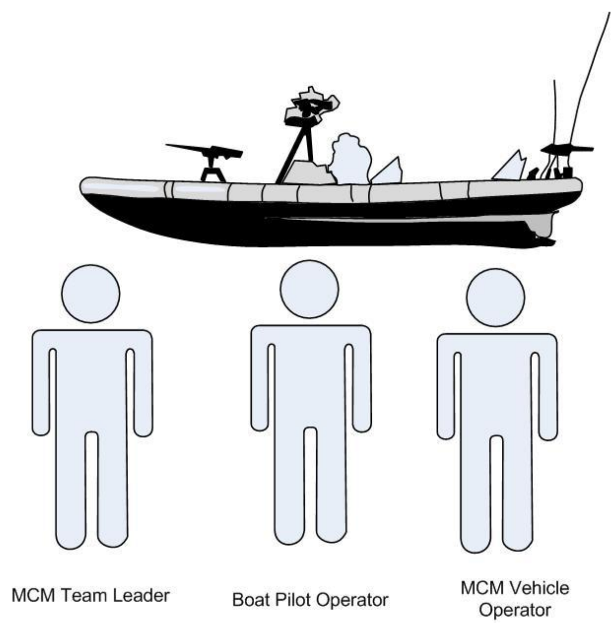

Figure 59. Local Operator Team

This figure depicts the minimum number of people to control the remote piloted SPUDS vehicle.

The local operator team consists of one person dedicated as a boat driver or pilot, a team leader who commands the team and communicates with the OTH MCM host ships, and a MCM Vehicle Operator who controls the SPUDS vehicle.

The MCM Local Operator (LO) system consists of the components shown in Figure 60. The system components consist of a low observable boat with all equipment necessary to run and operate the boat. The MCM vehicle radio is used to transmit and receive information from the MCM vehicle. The Control Panel Display and MCM vehicle control are used by the MCM vehicle operator to control SPUDS.

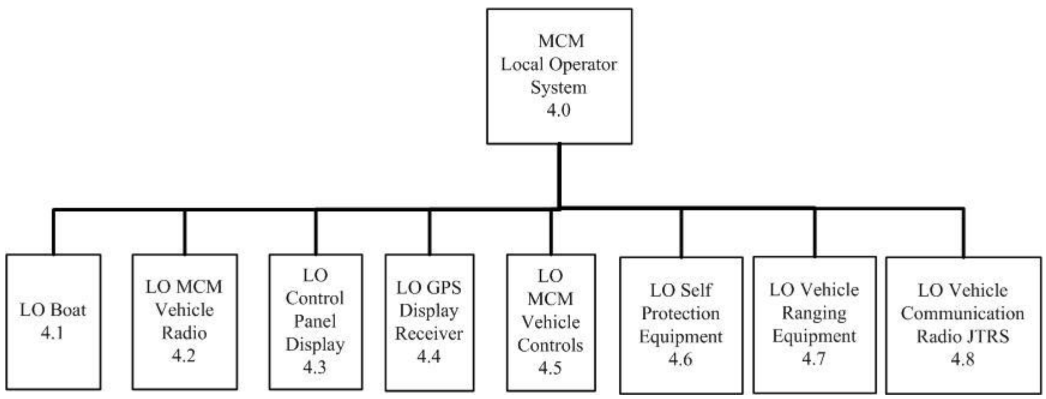

Figure 60. Alternative Three MCM Local Operator System Components

This figure depicts the components included in the MCM Local Operator System that operates the remote piloted SPUDS vehicle.

Conceptual operator controls for the SPUDS vehicle are shown in Figure 61. The control panel onboard the boat consists of a video display, which presents the optical images from either the front or the bottom cameras of the UUV. The video display also shows the outputs from the pressure and temperature sensors. A joystick and throttle to help steer the UUV and all the necessary functional controls to turn off and on the magnetic gradiometer, forward and side scan sonar, and optical sensors of the SPUDS vehicle. Additionally, the LO has a sonar that pings the MCM vehicle to estimate range to the vehicle and assist in driving the MCM vehicle. The LO has self-protection equipment and a JTRS or SINCGARS radio to talk to the MCM Host Platform.

Figure 61. Conceptual Local Operator Display Controls

This figure depicts the conceptual local operator display controls for Alternative Three.

The OTH Communication system component is accomplished through utilizing existing Navy assets such as an MH-60 or Fire-Scout UAV to provide the data-link communication. The UUV utilizes a VHF/UHF radio to communicate with the local operator. SPUDS will transmit location, heading, speed, and video to assist the local operator in driving the vehicle. This is done using a tether that is similar to the one used in Alternative Two.

The surface tether serves the important function of transmitting sensor and location data back to the LO. Due to the longer distance that is imposed by an OTH operation, the radio signals first are transmitted to an air platform in the area. From the air platform, the data is then relayed back to the Host Platform as shown in the tethered communications concept presented earlier in Figure 53.

The sensor suite of the SPUDS vehicle is composed of a magnetic gradiometers that has three magnetometer sensors, two optical sensors, and a sonar system consisting of a Forward Looking Sonar and two Side Scan Sonar systems.

The SPUDS vehicle has an interface box that performs dead reckoning navigation. The operator programs the vehicle at startup and allows sufficient amount of time for the rate gyros to

align themselves. The vehicle has no situational awareness functionality, and depends on the operator for guidance. Alternative Three does not have the ability to real time detect, classify, or identify a mine. The Advanced MCM system using this alternative must rely on PMA to detect, classify, and identify. Therefore, the SPUDS's MCM sensor data is stored via a recorder that must be retrieved at the end of mission and transferred back to the MCM ship. Figure 62 depicts the Alternative Three operational concept.

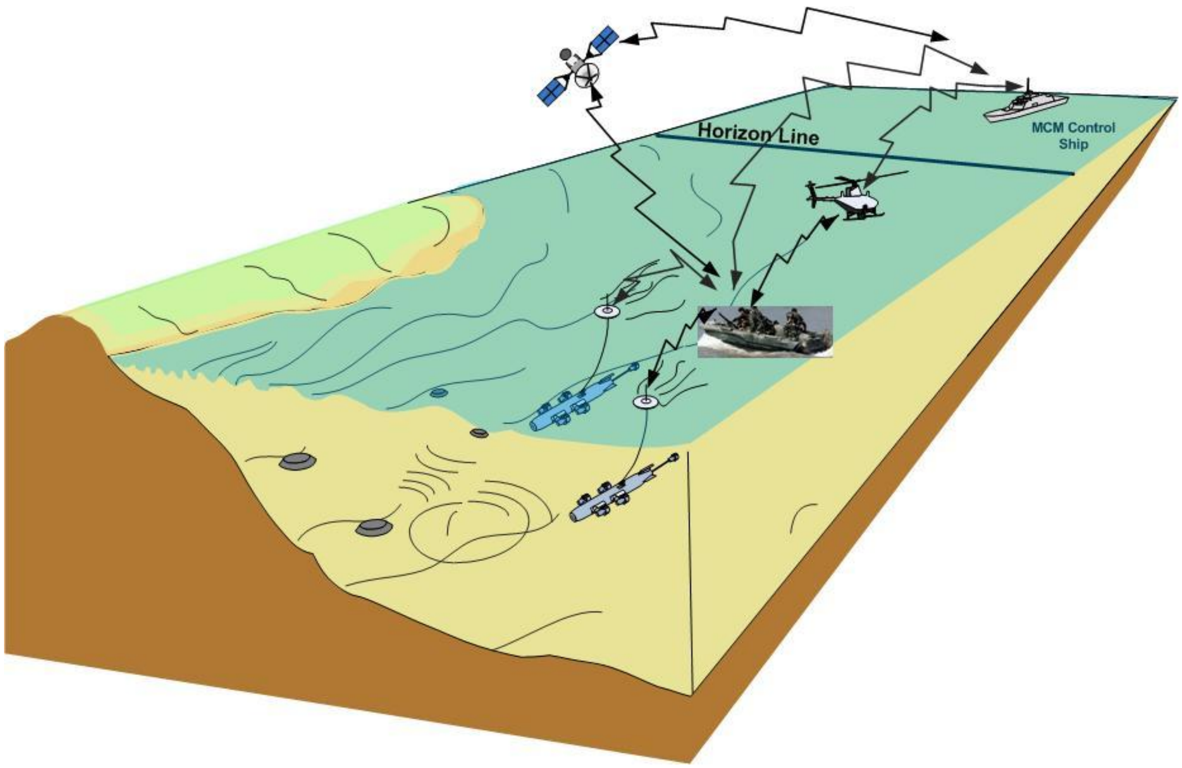

Figure 62. Alternative Three: Operational Concept

This figure depicts the operational concept of Alternative Three. The underwater vehicle relays search information back to a MCM ship using a surface-tethered radio link. The data is first transmitted to an air platform, and then relayed back to a MCM ship.

Figure 63 depicts the Alternative Three component diagram, breaking out the components of the system and how they relate to each other. The vehicle consists of a navigation system, communication system, power distribution system, MCM sensor system, and propulsion systems.

Figure 64 is a block diagram showing how Alternative Three's SPUDS vehicle functions as a remote controlled system. As shown in the figure, sensor data from the optical, magnetic, and side scan sonar's will be fed into the UUVs recorder.

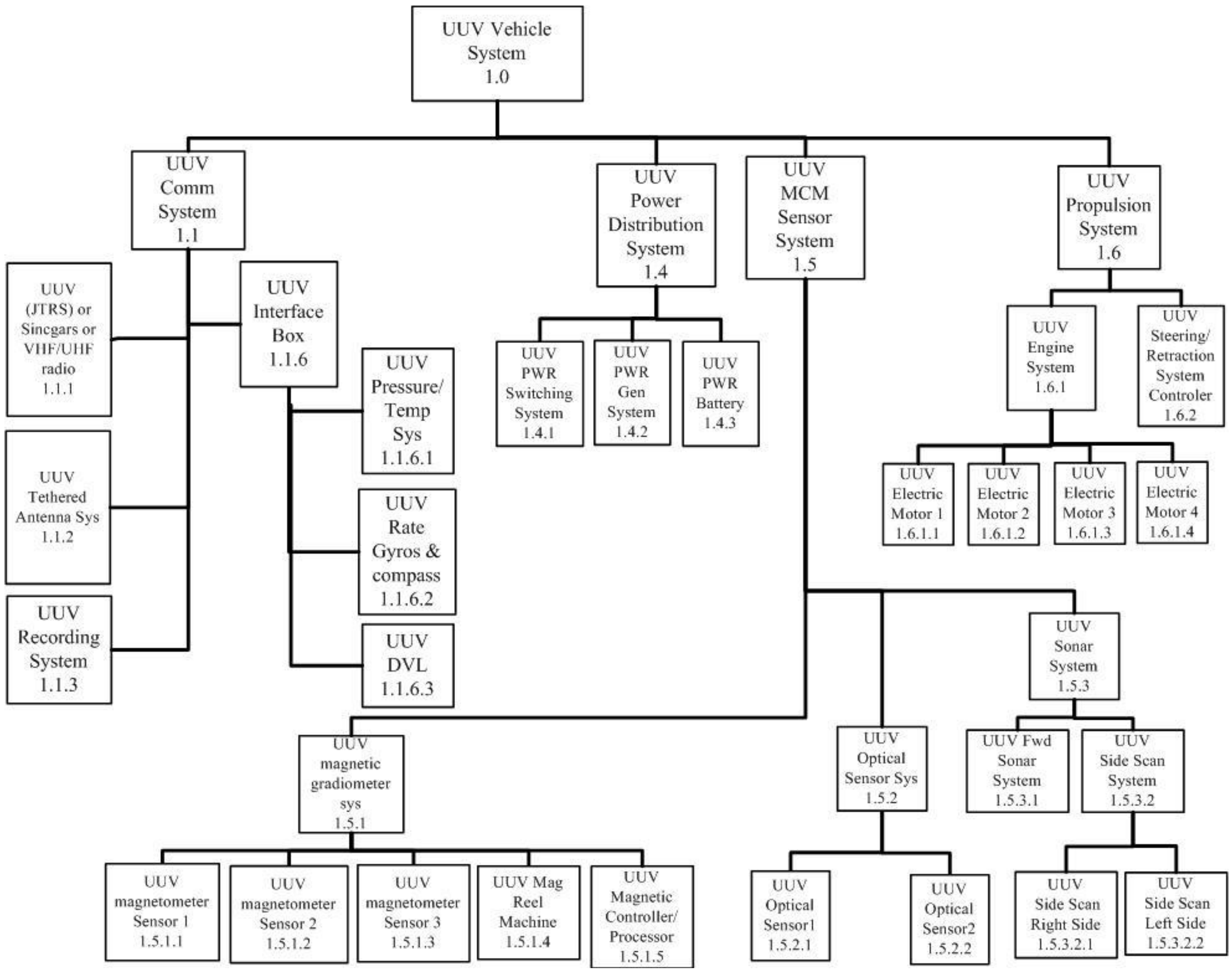

Figure 63. Alternative Three – Remote Control SPUDS Component Diagram

This figure depicts the component diagram of Alternative Three. The vehicle consists of navigation, mission processing, communication, power, sensor, and propulsion systems.

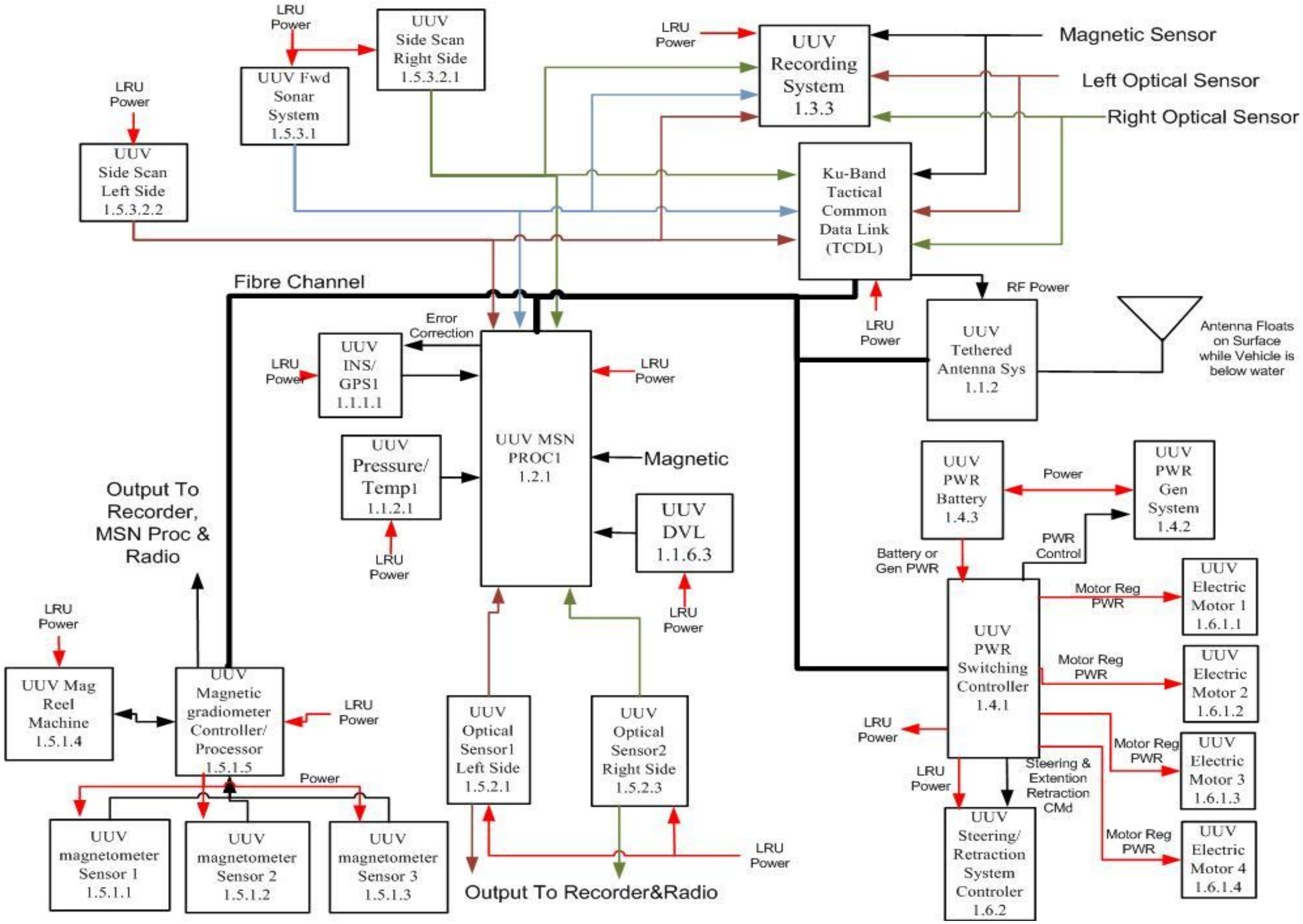

Figure 64. Alternative Three Conceptual Schematic Block Diagram of SPUDS

This figure depicts a block diagram model for Alternative Three. The figure shows the inputs and outputs to the system components. The different colors of inputs and outputs from the various components help trace power requirements and signals. The red color indicates a power input, while black and other colors show sensor inputs/outputs.

Figure 65, Figure 66, and Figure 67 depict the C2 and communication for the Host Platform as part of the MCM mission module. The communication system is composed of a server, a recorder, a switch and a video encoder. Since the Host platform does not receive MCM data real time, it is unnecessary to integrate a radio system. It is envisioned that communication with local operator team will be conducted through the ship's existing communication system. The server stores and retrieves mission data for the MCM recorder playback system. The switch provides routing of information and the video encoder encodes the analog video to enable it to be stored or routed to the operating stations.

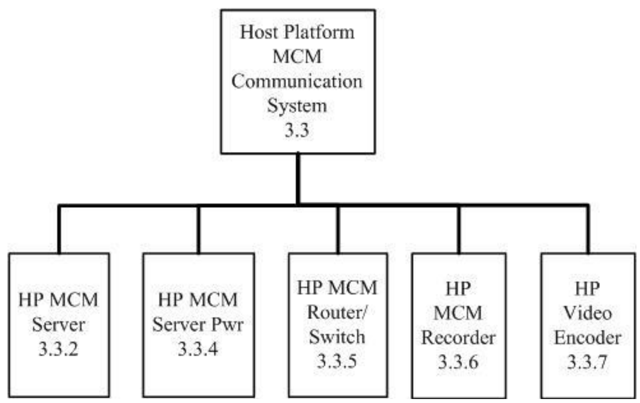

Figure 65. Alternative Three Host Platform Communication System Diagram

This figure depicts the components of the host vehicle platform.

Figure 67 depicts that the system requires six operating stations. Alternative Three requires four mission analysts (MAs) to perform real time analysis of sensor data coming from the SPUDS vehicle (this could be reduced to one if the Host Platform processing had auto target recognition functionality). One of the MA coordinates the communications with local operators. The Tactical Oversight position provides overall supervision of the MCM C2 system. This person determines routes, neutralization plans, and vehicle missions based on analysis of data from the MA positions. They develop the tactical map of the AO and communicate routes and mine field locations to the ship's command and control which is passed onto the amphibious force.

This alternative must have at least one operator present per UUV that is being used in a search operation. The UUV must also have at least one analyst that is fully dedicated to perform PMA for each vehicle.

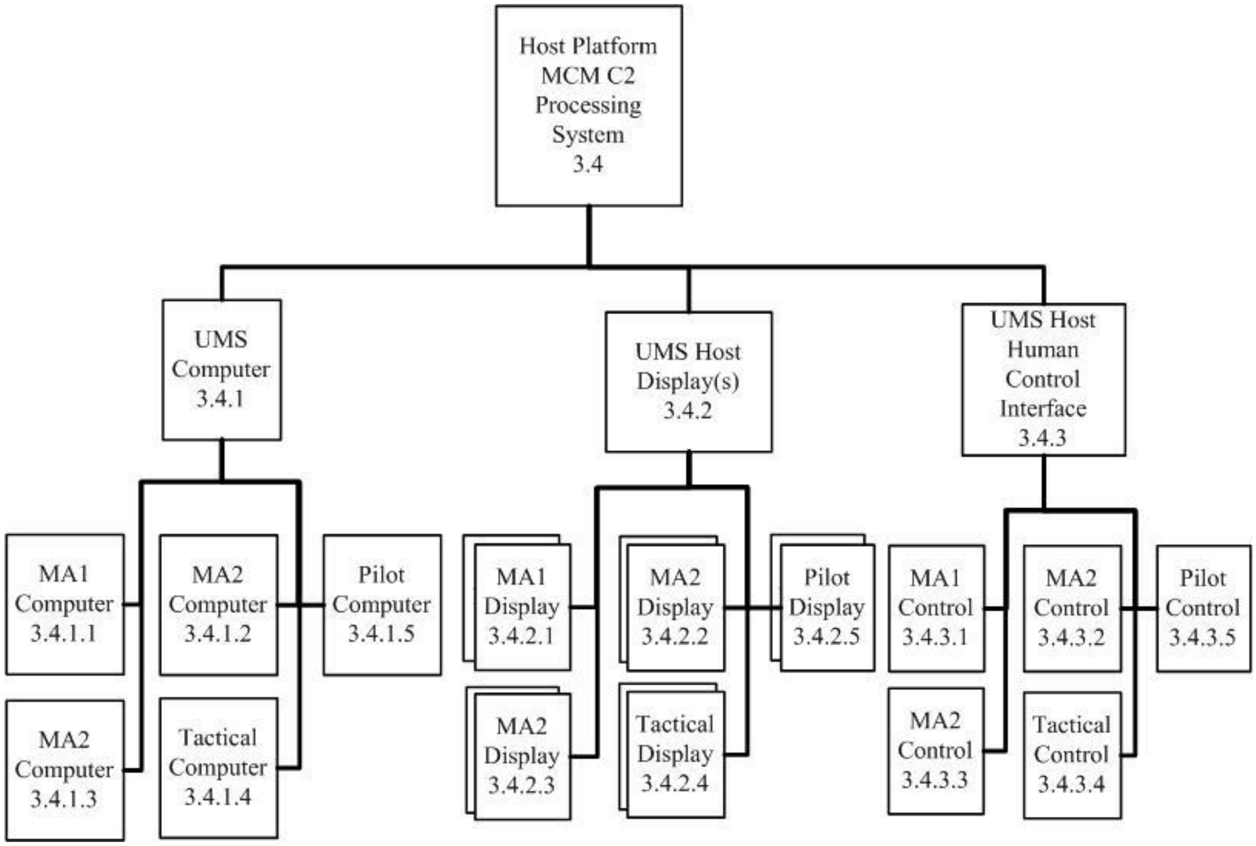

Figure 66. Alternative Three Host Platform C2 Processing Diagram

This figure depicts the components of the host vehicle platform MCM Command & Control Processing System.

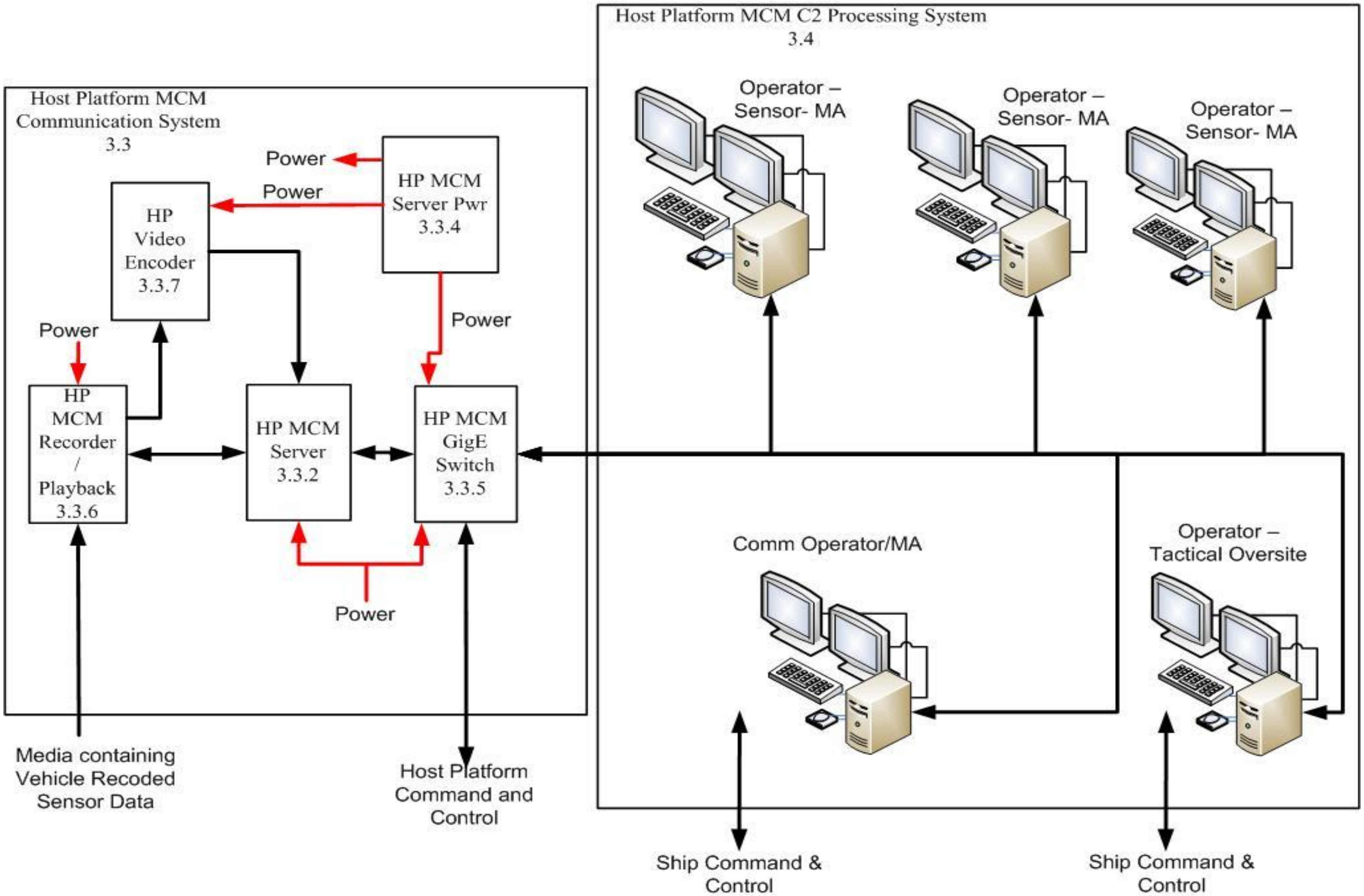

Figure 67. Alternative Three Host Platform C2 Schematic Block Diagram

This figure depicts the components of the host vehicle platform.

a. Alternative Three: Equipment & Personnel Summary

It takes six to eight people to operate Alternative Three in the AO. It is estimated that the maintenance personnel needed are at least 3 persons to provide maintenance for of the SPUDS power and propulsion system, mission LRU's, and maintenance of the Host Platform computer systems. It should be noted that Alternative Three can only control one SPUDS vehicle without increasing the manpower or Host Platform C2 and Local Operator equipment requirements. An addition of another vehicle will slow down the mission analysis due to several factors in coordinating retrieval of sensor data and performing analysis of the data. Table 16 is a summary of the equipment needed to deploy one SPUDS system in the Alternative Three configuration.

Table 16. Alternative Three Equipment List Summary

This table summarizes the Alternative Three components described in this section.

Platform	Equipment	Sub Component	Number
SPUDS Vehicle	Rate gyro/compass	N/A	1
	Depth Pressure Sensor	N/A	1
	Temperature Sensor	N/A	1
	DVL	N/A	1
	VHF/UHF Radio	N/A	1
	Radio Tether Antenna Sys	N/A	1
	Recording System	N/A	1
	Power Switching System	N/A	1
	Power Generation System	N/A	1
	Battery System	N/A	1
	Magnetic Gradiometer	Magnetic Controller Processor	1
		Magnetic Sensor	3
		Reeling Machine	1
	Optical Sensor	CCD/LED Sensor	2
	Sonar System	Forward Looking Sonar Transducer	1
		Left Side Scan Sonar	1
		Right Side Scan Sonar	1
	Engine Controller	N/A	1
	Electric Engine	N/A	4
	Steering Retraction System	N/A	1
Host Platform			
	Server	N/A	1
	Server Power Supply	N/A	1
	Router/Switch	N/A	1
	Recorder/Playback	N/A	1
	Video Encoder	N/A	1
	Operator Computers	N/A	5
	Displays	N/A	10
	Keyboards	N/A	5
	Trackball	N/A	5
OTH Communication	Conducted by Local Operator communicating mission information to Host Platform.	MH-60 Date link	As Rqd
		Fire-Scout - UAV	As Rqd
Local Operator Team	Boat	N/A	1
	MCM Vehicle Radio VHF/UHF	N/A	1
	Control Panel Display/Computer	N/A	1 per vehicle
	Throttle Controls	N/A	1 per vehicle
	Joystick	N/A	1 per vehicle
	Vehicle Ranging Equipment	N/A	1
	GPS/Navigator	N/A	1
	Vehicle Communication Radio	N/A	1 per vehicle
	Self Protection Equipment	50 caliber MG or M240 & Ammo	2
		Protection Vests	Per Person
		Personal Weapons & Ammo	Per Person
		1st Aid	Per Person
		Helmets	Per Person

b. Alternative Three: Components Mapping to Functions & Requirements

Table 54 and Table 55 of Appendix E contain the component mapping of Alternative Three to the associated functions and requirements previously defined in this report to verify that the system has been properly designed. It should be noted that the generic mapping was completed in Table 9 and Table 10 of this report.

I. SUMMARY OF ALTERNATIVES

Table 17 provides a high level comparison of the alternatives' capabilities and components.

Table 17. Alternative Comparisons

This table provides a comparison of the different alternatives.

	Alternative One	Alternative Two	Alternative Three
Autonomy	Fully Autonomous	Tele-Operate	Hybrid Remote/ Tele-Operate
OTH Communication	Fully Autonomous RF Buoy Network	Airborne RF Data-Link - TCDL	RF Voice Communication with Local Operator using SATCOM or data link via airborne platform
Vehicle Communication	Underwater Acoustic	RF TCDL - Tethered Antenna	RF UHF/VHF Tethered Antenna
Bandwidth Communication with Vehicle	Low-Medium Bandwidth - Communication requires data words giving vehicle position, mine & mine type location status.	Extremely High Bandwidth - Need to transmit All Vehicle Sensor data to Host Platform	High Bandwidth - Vehicle transmits video to Local Operator
Number of People to Operate Advance MCM System	Two operators to operate anywhere from one to many vehicles simultaneously	6 people for two vehicles 12 people for 4 vehicles 18 people for 8 vehicles - personnel requirement adds 6 people every 2 vehicles added	8 people per vehicle 11 people per two vehicles 16 people per three vehicles 19 people per four vehicles 24 people per five vehicles - Add 3 people on odd number of vehicles and add 8 on even number of vehicles
Processing MCM data for Mine Detection, Classification, identification, location	Vehicle - Real time Auto Target Recognition (ATR) Mission Analysis (MA)	Host Platform - Real Time MA	Host Platform PMA
Vehicle Processors	3	1	None - Interface Box
Vehicle Navigation Sensors	3	1	1
Host Platform Operator Stations	2	6 per 2 vehicles	5 per 2 vehicles
Optical Sensors	4	2	2

V. MODELING AND SIMULATION

Modeling and simulation for this project used the previously defined MOEs of Area Coverage Rate, number of undetected mines, and stealth, as a technical evaluation tool to compare the system alternative architectures. Modeling of the architectures utilized both Microsoft Excel and *Imagine That*'s ExtendSIM depending on what combination of input and output characteristics were under evaluation. Excel was used to analyze and model factors regarding stealth and navigation and was used to graph and perform a statistical analysis of the results. ExtendSIM was used to model the probability of detection and classification, and the delays associated with the search method for each alternative. The nature of the ACR and number of undetected mines lends them to mathematical models; however, stealth was more difficult to define.

A. MEASURES OF EFFECTIVENESS MAPPED TO FUNCTIONS

To determine the parameters to be modeled, the developed metrics were mapped to the defined functions. This process defined the relationship of each system metric to system functions and outlined how the parameter was to be modeled.

Table 18 contains the mapping between the functions and the metrics with the parameters that were considered in the model. After an analysis the functions of Deploy, Search, Detect, Classify, Identify, and Communicate were modeled. The functions Search, Detect, Classify, Identify, and Communicate were included since they are part of the bounded system. Although the Deploy function was outside the bounded system, it was selected since it had an effect on stealth. The functions of Perform Planning, Recover, Transit, and Receive Maintenance are outside the bounded system. These functions were reviewed, but since a significant effect on the metrics was not found, they were not modeled. Although the Engage function was part of the bounded system, a specific model was not created. The Engage function could be considered completed by either localizing a target so that it may be avoided or neutralizing the target. It was determined that if the Engage function was completed for localizing the target, it would not add time to the DTE sequence. Since our recommendation is that the neutralization be performed by a separate system, a model was not created for that system. It is recommended that this concept is researched further by a different cohort.

Table 18. Mapping of Functions to Metrics

Table depicts linking between system functions, MOEs, and modeling parameters used.

Top Level Function	1st Level Sub function	SUB Function	Input Parameters	ACR	Undetected mines	Stealth
Deploy- FDE.8	Deploy from Sub-surface Craft	FDE.8.1	System Deployment Timeframe			**X**
	Deploy from Surface Craft	FDE.8.2	System Deployment Timeframe			**X**
	Deploy from Aircraft	FDE.8.2	System Deployment Timeframe			**X**
Search – FS.7	Follow Search Commands	FS.7.3	Time to Navigate	**X**		
			System Exposure Above the Waterline			**X**
			Vehicle Ordered Speed	**X**		
			Support Equipment Required			**X**
			Environmental Current speed	**X**		
			Amount of time vehicle stops to communicate	**X**		
			Data Rate Utilized			**X**
Detect – FD.1	Receive Info. from Sensors Indicating Contact in Area	FD.1.1	Sensor Range		**X**	
			P_dP_c		**X**	
			Time to Detect and Classify Mine	**X**		
Classify – FC.2	Process Sensor Input	FC.2.1	P_dP_c		**X**	
			Time to Detect and Classify Mine	**X**		
Identify – FI.3	Determine if Mine like Contact is a Bottom Mine	FI.3.1	P_dP_c		**X**	
			Time to Detect and Classify Mine	**X**		
	Determine if Mine like Contact is a Moored Mine	FI.3.2	P_dP_c		**X**	
			Time to Detect and Classify Mine	**X**		
	Determine if Mine like Contact is a Drifting Mine	FI.3.3	P_dP_c		**X**	
			Time to Detect and Classify Mine	**X**		
	Determine if Mine like Contact should be Avoided	FI.3.4	P_dP_c		**X**	
			Time to Detect and Classify Mine	**X**		
Communicate - FCO.6	Receive Communications	FCO.6.1	Data Rate Utilized			**X**
			Amount of time vehicle stops to communicate	**X**		
	Transmit Communications	FCO.6.2	Data Rate Utilized			**X**
			Amount of time vehicle stops to communicate	**X**		

Top Level Function	1st Level Sub function	SUB Function	Parameter	ACR	Undetected mines	Stealth
Deploy- FDE.8	Deploy from Sub-surface Craft	FDE.8.1	System Deployment Timeframe			**X**
	Deploy from Surface Craft	FDE.8.2	System Deployment Timeframe			**X**
	Deploy from Aircraft	FDE.8.2	System Deployment Timeframe			**X**
Search – FS.7	Follow Search Commands	FS.7.3	Time to Navigate			
			System Exposure Above the Waterline			**X**
			Vehicle Ordered Speed			
			Support Equipment Required			**X**
			Environmental Current speed			
			Amount of time vehicle stops to communicate			
			Bandwidth Utilized			**X**
Detect – FD.1	Receive Info. from Sensors Indicating Contact in Area	FD.1.1	Sensor Range		**X**	
			P_dP_c		**X**	
			Time to Detect and Classify Mine			
Classify – FC.2	Process Sensor Input	FC.2.1	P_dP_c		**X**	
			Time to Detect and Classify Mine			
Identify – FI.3	Determine if Mine like Contact is a Bottom Mine	FI.3.1	P_dP_c		**X**	
			Time to Detect and Classify Mine			
	Determine if Mine like Contact is a Moored Mine	FI.3.2	P_dP_c		**X**	
			Time to Detect and Classify Mine			
	Determine if Mine like Contact is a Drifting Mine	FI.3.3	P_dP_c		**X**	
			Time to Detect and Classify Mine			
	Determine if Mine like Contact should be Avoided	FI.3.4	P_dP_c		**X**	
			Time to Detect and Classify Mine			
Communicate - FCO.6	Receive Communications	FCO.6.1	Bandwidth Utilized			**X**
			Amount of time vehicle stops to communicate			
	Transmit Communications	FCO.6.2	Bandwidth Utilized			**X**
			Amount of time vehicle stops to communicate			

B. MODELING PARAMETERS MAPPED TO ALTERNATIVES

Once the functions were mapped to the metrics and the modeling parameters were determined, the modeling parameters were mapped to the components of the alternatives to ensure that the model accounted for any differences in the architectures that would affect the metrics. Due to the complexities of factors present during the search and detection of sea mines, it was determined that only the differences in the alternatives that affected the metrics would be modeled. With the limited time and resources available for the modeling and simulation, the focus of the models was placed on the factors that would be best able to allow a decision among the alternatives. Table 19 contains the definitions for the parameters used to create the models. The input parameters were chosen since they are the characteristics which dominate the behavior of the architectures in the environment.

Table 19. Definition of Input Parameters

This table shows the definitions of the parameters used in the modeling and simulation portion of the project.

ACR Parameters	Definition
Vehicle Ordered Speed	The velocity at which the vehicle was ordered to travel. With no current this is equal to the actual speed. This was an input variable into the Excel navigation model which was used to determine the time to navigate.
Environmental Current speed	The velocity of the water surrounding the MCM vehicle. This was an input variable into the Excel navigation model which was used to determine the time to navigate.
Amount of time vehicle stops to communicate	The amount of time the vehicle requires a suspension of the search for communication. This was an input variable into the Excel navigation model which was used to determine the time to navigate.
Time to Navigate	The amount of time the vehicle takes to travel though the entire minefield. This includes any stops to determine location, and time to correct the vehicle's course. This was an output of the Excel navigation model and an input into the ExtendSIM model. This was used to determine the ACR.
Time to Detect and Classify Mine	The amount of time between the sensors detecting an object and the object being classified as either a mine or a non-mine. This was an input into the ExtendSIM model.
Undetected Mines Parameters	**Definition**
Sensor Range	The usable range of the sensors from the vehicle. This was an input to the Excel navigation model to determine which mines would be excluded from the ExtendSIM model due to navigation error.
P_dP_c	The probability of detecting and correctly classifying targets within a search pattern. This was an input to the ExtendSIM model.
Stealth Parameters	**Definition**
System Exposure Above the Waterline	The amount of the system in the AO that would be observable above the waterline during the search period. This was an input to the stealth analysis to determine the system exposure above the waterline rating.
Data Rate Utilized	The rate at which the required data is transferred during the search period. This was an input to the stealth analysis to determine the data rate utilized rating.
Support Equipment Required	The amount of equipment in the AO when the system is operating. This was an input to the stealth analysis to determine the support equipment required rating.
System Deployment Timeframe	How early the system can be deployed. This was an input to the stealth analysis to determine the system deployment timeframe rating.

When considering the hydrodynamics of the VSW range, since the shape, the power system and propulsion system were the same for all the alternatives a detailed model was not constructed. It was assumed that all the SPUDS would be able to accelerate and maintain their speed equally. Along the same lines, however, the steady state current would have an effect on the SPUDS when navigation was considered. If the SPUDS was unable to correctly determine its location it would be possible for a steady state current to push the SPUDS off course. This would increase the time to navigate since the SPUDS would periodically need to adjust its course to return to the desired track. The number of undetected mines was also affected if the error in navigation caused the mine to be outside the sensor range. The navigation error would also affect the reacquire time for neutralization, but since the neutralization function is not considered in the bounded system.

In considering the performance of the sensors, many of the sensors are the same, therefore, the focus of the model turned to the ability to use the sensor data to correctly identify an object as either a mine or a non-mine. Since it is possible the system could detect a mine but not correctly classify it as a mine, the P_dP_c is used as one value. If we assume that any object within the sensor range has a probability of detection of 100%, the system's inability to classify the object correctly would be equivalent to not detecting the object in the first place. The sensor range was used as the distance at which the ability to correctly classify the object was unlikely.

When considering the alternatives as they related to stealth, it was assumed that since the SPUDS exterior would look the same, they would be equally easy to observe in identical situations. The behavior of the system, however, would allow the SPUDS or other portions of the system to be easier to observe.

For the stealth analysis, all portions of the system which could be observed from the AO were considered in the analysis; for the ACR and the undetected mines the portions of the system outside the AO were considered when they would affect the behavior of the SPUDS in the AO. This behavior includes any actions taken by an operator that would cause a particular alternative to act differently from the other alternatives. Table 20 maps the parameters that were modeled to the individual SPUDS components that varied among the alternatives.

Table 20. Mapping of Parameters to Components

This table shows a mapping of the parameters to the system components and the metrics affected. A=ACR, S=Stealth, and U=Undetected mines. The blank spots indicate that either there are no differences in the architectures or these have no affect on the parameters.

Input Parameters	**System Components**					
	UUV System					
	UUV NAV Sys	UUV MCM Proc	UUV Comm Sys	UUV Propulsion Sys	UUV PWR Sys	UUV Neutralizer
Vehicle Ordered Speed	A					
Environmental Current Speed	A					
Amount of time vehicle stops to communicate			A			
Time to Navigate	A					
Time to Detect and Classify Mine		A				
Sensor Range		U				
P_dP_c		U				
System Exposure Above the Waterline	S					
Data Rate Utilized			S			
Support Equipment Required	S	S	S	S	S	S
System Deployment Timeframe	S	S	S	S	S	S

C. STEALTH ANALYSIS

Stealth modeling and simulation evaluated each MCM system alternative's ability to remain undetected. The MCM system includes the SPUDS, Host Platform (located OTH), and any necessary support craft to include; MH-60 helicopters, the UAV Fire-Scout, and a Local Operator High Speed Boat (LOHSB).

Stealthiness is defined as "slow, deliberate, and secret in action or character" (Merriam-Webster Dictionary, 2012). The stealth metric unit of measure is Probability of Detection by Enemy, expressed as a percentage. Since this value was difficult to model, an analysis was performed on the alternatives using general stealth parameters to rank each alternative's level of stealth. The stealth parameters defined a way to address stealth with the ranking indicating which alternative would have the lowest Probability of Detection by Enemy. The stealthiest alternative was determined by evaluating each system on the following four parameters:

1. System exposure above the waterline
2. Data rate utilization
3. Support equipment required
4. System deployment timeframe

1. System Exposure above the Waterline

System exposure above the waterline was analyzed by evaluating each alternative's overall component footprint. For example, Alternative One required the use of an RF Buoy Network, whereas Alternative Two and Alternative Three required the support of a MH-60 Helicopter or Fire-Scout to conduct OTH communications. Therefore, Alternative One had the least system exposure above the waterline and was considered the stealthiest MCM system based on system exposure above the waterline.

Consideration was also given to the duration of time in which the alternative systems would be exposed above the waterline to conduct communication. However, there was found to be little difference between alternatives as the exposure for each platform remained constant for the duration of the mission. Therefore, the duration of time in which the alternatives would be exposed above the waterline was not considered for this analysis.

a. Alternative One Rationale

Alternative One is a fully autonomous system which utilizes a fully autonomous RF buoy network for OTH communications and an underwater acoustic system for vehicle to vehicle communications. The RF buoy network would be present for the entire mission but the surface exposure of these buoys above the waterline would be minimal.

Alternative One would be deployed without the additional support of surface platforms to support data transfer. Since this alternative possesses an advanced GPS system, this would allow the system to remain sub-surfaced for extended periods of time and would reduce the number of surfacing events required during the mission. Because Alternative One was designed with onboard data processing and targeting capability, the vehicle conducts identification and classification tasking real-time in the AO. Once targets are processed, the vehicle would surface periodically to data burst information back to operators on the Host Platform.

b. Alternative Two Rationale

Alternative Two, being tele-operated, would utilize a tethered antenna system to connect the SPUDS vehicle to an airborne RF Data-Link TCDL system for OTH communications. The airborne RF-Data-Link TCDL system would requires the support of an MH-60 or UAV Fire-Scout to conduct OTH communications throughout the mission. Either of these aerial systems would have a larger system exposure than Alternative One.

c. Alternative Three Rationale

Alternative Three, being a remote/tele-operated system, would utilize a tethered antenna and RF Voice Communications with local operators using SATCOMS or data links via airborne platforms like the MH-60 or Fire-Scout for OTH communications. Alternative Three also requires the support of a Local Operated High Speed Boat (LOHSB). The addition of the LOHSB to Alternative Three's overall MCM system increases the system's exposure to be larger than that of Alternative Two.

d. System Exposure Results

The stealth rating of each alternative based on system exposure above the waterline. The order of stealthiness for these platforms from most stealthy to least stealthy is as follows; Alternative One, Two, then Three.

2. Data Rate Utilized

The data rate utilized part of the stealth analysis examined the amount of required data transfer for each alternative to complete the mission. The larger the data rate, the more likely an alternative would be detected while conducting the MCM mission. For the bandwidth utilized, first the type of data required to be transmitted was identified, and based on the type of data required, a bandwidth value of low, medium, or high was assigned to the alternative.

a. Alternative One Data Rate Analysis

Alternative One possesses real time auto target recognition (ATR) and Mission Analysis capabilities (MA). These functions enable SPUDS to detect, classify, identify, and locate mines without the assistance of the Host Platform. Therefore, SPUDS and host platform need to transmit minimal amounts of data (low data rate) through a fully autonomous RF buoy system to complete the mission. Alternative One would require the transmission of the vehicle location, health status, target location/identification/classification, and high level mission changes to the search plans. This information would not require a high data rate because it can be transferred in the form of text. Additionally, because the system is autonomous it does not require data transmission on a continuous basis. Instead, Alternative One would be able to intermittently transmit data to the host platform reducing the chances of a transmission being intercepted by the enemy.

b. Alternative Two Data Rate Analysis

Alternative Two transmits all sensor data back to the host platform through the use of an airborne RF data link system. Therefore, Alternative Two would be required to transmit high data rates on a continuous basis. The requirement for a high data bandwidth and continuous transmissions means Alternative Two's transmissions are more likely to be detected than Alternative One's. Alternative One would therefore be considered stealthier than Alternative Two.

c. Alternative Three Data Rate Analysis

Alternative Three would send video data to a local operator continuously but would not transmit video data OTH. Instead the data is recorded on SPUDS and downloaded and analyzed on the host platform following the completion of the mission. The communication system used to conduct SPUDS communications to the LOHSB would be RF UHF/VHF. The communication system utilized for OTH communications would be RF Voice Communications with the local operator using SATCOM or data link via the airborne platform for mission direction. The continuous video feed to the local operator requires a high data rate. Since Alternative Three does not send all of its sensor data back to the local operator and stores this

information in the onboard system, Alternative Three was found to be stealthier than Alternative Two based on total bandwidth utilized.

d. Data Rate Analysis Results

Based on the data rate transmitted the stealthiest MCM system was Alternative One followed by Alternative Three, and then Alternative Two.

3. **Support Equipment Required**

The support equipment required also affects the stealth of the overall system. Support equipment affects the surface exposure above the waterline, acoustic detection, electromagnetic detections etc. Due to the limited information available and the classification level of this analysis, electromagnetic and acoustic signatures were not analyzed. The type of support equipment required, however, provides an unclassified method for addressing these detection parameters.

a. Alternative One Support Equipment

Alternative One would require a helicopter, plane, surface craft, or subsurface craft to deploy the UUV and the RF Buoy Network. Once deployed, the system would not require any additional support equipment beyond the RF buoy network. Therefore, minimal support would be needed, making the system very stealthy.

b. Alternative Two Support Equipment

Alternative Two could also be deployed in a similar manner as Alternative One. However, the system would not require the use of an RF buoy system, but instead requires a MH-60 or Fire-Scout for OTH communications during the mission. Although not necessarily in the AO, the air support would increase the overall presence during the execution of the mission thereby reducing the stealth of the MCM system. Because Alternative Two requires the MH-60 or Fire-Scout for OTH communications throughout the mission, Alternative Two was less stealthy than Alternative One.

c. Alternative Three Support Equipment

Alternative Three would require the most support of the alternatives. The system would require the support of a MH-60 or Fire-Scout for the entire mission and would require a LOHSB near the AO for the entire mission. Alternative Three was found to be less stealthy than Alternative Two.

d. Support Equipment Results

Alternative One was found to be the stealthiest MCM system followed by Alternative Two, and then Alternative Three in relation to support equipment required.

4. System Deployment Timeframe

The final parameter analyzed was the system deployment timeframe. Early deployment will increase stealth of the system by decreasing the overall presence in the area of interest while the mission is underway. Alternative Two and Three cannot be deployed prior to conducting the mission because both these alternatives require support platforms to operate the systems. Based on system deployment timeframe, Alternative One was the stealthiest system followed by Alternative Two and Three being equally as stealthy.

5. Stealth Summary

The analysis of the stealth MOE took into consideration the scoring of the four components of stealth for each system, and determined that the stealthiest alternative was Alternative One followed by Alternative Two, and then Alternative Three. This information was utilized to aid in the selection of the best alternative for the future system recommendation. The ranking of the alternatives in order of stealth is shown in Table 21.

Table 21. Ranking of Alternatives

This shows the ranking of the alternatives based on Stealth. As a result, Alternative One is determined to have the most stealth of all the alternatives.

Stealth Component	Alternative One	Alternative Two	Alternative Three
System Exposure Above the Waterline	1	2	3
Data Rate Utilized	1	3	2
Support Equipment Required	1	2	3
System Deployment Timeframe	1	2	2
OVERALL RANK	1	2	3
	Note: 1-most stealthy and 3-least stealthy		

D. MODELING ACR AND NUMBER OF UNDETECTED MINES

1. Method of Modeling

For all alternatives, the same methodology was used to create the models. In order to determine the amount of time the vehicle took to navigate the DRM minefields and the error in the location based on the various navigation systems, an Excel Visual Basic Macro was used. The prototype Excel macro was provided by NPS Professor Paul Shebalin (Shebalin, 2012). This Excel macro was used to control the ordered speed of the vehicle, the water current speed, and the range of the sensors. The macro was programmed with the effect of water current on the vehicle speed, and the error in vehicle location based on the navigation system. The vehicle location, after accounting for navigation error, was used to determine if a mine would be in range of the sensors, and how long the vehicle took to travel from one mine-like contact to another.

The ExtendSim model assigned a delay to each contact equal to the time when the Excel macro determined the mine was intercepted. As each contact was selected, the ExtendSim model then added a delay which was equal to the time required for detect and classify functions. When the detect and classify delay was completed, the contact was chosen as either correctly detected and classified, or missed based on the P_dP_c. An additional delay was added to Alternative Three to allow for the PMA. The ExtendSim model performed 1000 simulations. The data was collected and analyzed in Excel. A further discussion of the model is in Appendix F.

2. Assumptions

For the Excel macro, all the architectures were set to 1.64 yards/sec, or 1.5 m/s, for their ordered speed. This value was based off the speed that the MK-18 system would need to survive a collision. This speed is 1.5 m/s (Pollitt, 2011). The assumption was that if the MK18 UUV must survive a collision of 1.5 m/s, then it is likely the vehicle would normally be traveling at that speed. Since the area designed as part of the DRM was measured in yards, this speed was converted and rounded to 1.64 yds/s.

In order to verify our planned swath width, the ACR was calculated by taking the total distance the vehicle would travel in the minefield. Based on a 1.64 y/s speed, the time to complete this trip was calculated to be 1 hr and 9 minutes. This would give an ACR of 0.0506 n.m.^{2}/hr. This was compared to the value that was determined for the MK18 UUV during testing performed by Johns Hopkins University (JHU) as 0.25 km^2/hr (Pollitt, 2011). Converting the JHU value into English units, the value is approximately 0.0726 n.m.^{2}/hr. The difference between the calculated ACR and the JHU ACR could be based on the actual speed of the MK18 UUV, or differences in the distance the MK18 UUV traveled for their search when compared to

the simulated search. The final difference could be explained by a difference in their definition of ACR when compared to what was chosen for our simulation. These values are presented in Table 22.

Table 22. Values Used in the Production of the Models

The table shows some of the values used when determining the validity of the models.

Parameter	JHU values	311-103O Simulated
Vehicle Speed	1.5 m/s (1.64 y/s) estimated	1.64 y/s
ACR	0.25 km^2/hr (0.0726 $n.m.^2$/hr)	0.0506$n.m.^2$/hr
Area covered	4.85 km^2 in four days	500 yards by 500 yards
Swath width	40 meters	40 yards
Sensor Range	N/A	70 ft

In the DRM minefields, it was decided that the swath for each pass of the architecture would be 40 yards. Comparatively, the MK18 UUV testing by JHU used 40 meters as a swath (Pollitt, 2011). Since the DRM states the minefield area is 500 by 500 yards, this analysis kept the swath as yards in order avoid possible errors in the conversion. Using a swath of 40 yards, the range of the sensors was set to 70 ft in the model. This would have the simulated vehicle cover an area of ±20 yards on either side of the desired path, plus a 10 ft overlap for each vehicle pass. It is assumed that the sensors would be able to detect mines at a greater distance, but in complex environments the sonar shadows and other measurement noise in the environment would greatly reduce the P_dP_c. This range also allows for errors in the navigation to show up as mines not detected.

The tidal current in the environment was selected based on what was documented in the DRM; this was set to 2.5 kts. The direction of the current was set to 10 degrees off the X-axis of travel of the modeled architecture and was varied in the model. The effect the angle had on the vehicle was that the component of the current that was in the direction of travel was added to the vehicle's forward speed. When the vehicle's direction of travel was against the current, the vehicle's forward speed was reduced. Any tangential component to the current caused a reduction in the line of travel speed. It was assumed that in order to stay on course the vehicle would need to provide an equal and opposite force to counteract the tangential forces.

3. **Creating and Validating the Model**

During the creation of the models for the ACR and Undetected mines, one concern was to be able to understand if the answers that were received were reasonable. Whenever possible, values from the MK18 UUV testing were used as a comparison. If there were factors that did not have a real world marker to be judged against, the results were analyzed to validate the model.

One of the first factors to be validated was navigation. While the models were being created, the values for the vehicle's actual location were compared to the desired course. These values were plotted and reviewed to ensure that the desired results were achieved.

The next factor that was validated was the speed of the vehicle. This was done by calculating the time the vehicle should take to complete each DRM minefield without any current. When the model was executed, the amount of time to complete the navigation was compared to the calculated value. If the time to maneuver the minefield was similar to the calculated value it was deemed to be validated.

When the effects of current were added to the model, the current was first set to 0 knots, and a simulation was performed to gain a baseline. The current was then set to 2.5 knots with an angle of 0˚. Another simulation was performed, and it was compared to determine if the current had the appropriate affect. The simulation was repeated with the current's angle set to 90˚, 180˚ and 270˚ to ensure the vehicle's speed was reacting properly.

The last factor to be validated was P_dP_c. Since this was simply a percentage, the results were reviewed to verify the mean of the detected objects approximated the probability.

4. **Modeling Alternative One**

The navigation component for Alternative One was modeled as three systems, each with an error of 1% of the true location. This assumption was based on Panish and Taylors's paper, which showed that highly accurate INS systems using Doppler Velocity Logs (DVL) can result in highly accurate navigation (Panish & Taylor, 2011). These three values were averaged and the value was used as the actual location. This error was calculated every time the simulation moved the vehicle.

Since the alternative's communication takes place while the vehicle is in motion, the time to communicate has no affect on the ACR. Therefore this time was not added to the ACR.

The P_dP_c was set to 0.9. Because the sensor packages for all alternatives consist of very similar equipment, it was assumed that the value for the probability of detection would be equal for all systems. Because there are extra optical sensors on Alternative One, and the classification of the mine is performed by algorithms, it was assumed that in 10-15 years the P_dP_c would be at least as good as the MK-18 Increment IV Objective value of 0.9 shown in the draft MK18 Consolidated Requirements Document (CRD) (PMS 408, 2011). Although the CRD is a draft, prospective details in this document were given to this cohort as perspective requirements and performance expectations for future system development.

Determining the amount of time it will take any system to detect and classify a mine in the type of environment stated in the DRM is a difficult task. Informal top level discussions were held with Dr. Jake Wetzel (BCI Inc.), a subject matter expert in human systems integration working currently on MCM issues. During these discussions it was discovered that an actual time was unable to be determined. The discussion showed that it is generally thought that the time to complete the task is situation dependent (Wetzel, 2012).

However, since a time was required for determining the ACR, an assumption was made that the mean time to detect and classify was 60 seconds with a standard deviation of 20 seconds using a lognormal distribution. The assumption for the amount of time was based on the assumption that a computer with correctly programmed image detection algorithms in 10-15 years would be quicker than a human, with much less variation in the amount of time to complete the task. The distribution was based on the task of classifying a mine being of unequal frequency and duration (Blanchard & Fabrycky, 2011).

Because the times for the ACR were not able to be accurately predicted a sensitivity analysis was performed. In order to evaluate the performance of the alternatives against each other, the same time and standard deviation combinations were used. The mean times for detect and classify were selected to be 60 s, 120 s and 240 s. These were combined with the standard deviations of 20 s, 40 s, and 60 s. This presented 9 different combinations for each alternative. 1000 simulations were performed for each.

5. Modeling Alternative Two

The navigation system of this alternative consists of a GPS system that is backed up with a DVL and INS system. The technical specifications of the Photonic Inertial Navigation System (PHINS) system shows this set up would be three times better than GPS alone (IXSEA, 2011). Since a standard GPS can have an error between 1-10 meters, and the INS can improve this by three times, the navigation error was modeled as a normal distribution around the desired course with a standard deviation of 1.111 ft (Snively, 2011; IXSEA, 2011). The error was calculated every time the simulation moved the vehicle.

Since this vehicle is in constant contact with the Host Platform, the alternative does not stop to communicate so times associated with communications were not factored into the ACR.

The P_dP_c was set to 0.8. Since the sensor packages for all alternatives consist of very similar equipment, it was assumed that the value for the Probability of Detection would be equal for all systems. Without the number of optical sensors Alternative One has, and the fact the classification would be performed real time by a human, it was assumed that the P_dP_c would be at least equivalent to the MK18 UUV Increment II Threshold shown in the CRD (PMS 408, 2011). This value is 0.8 with the limiting factor being the ability for a human or group of humans to recognize the mines based on the data provided.

Determining the amount of time it takes to detect and classify a mine in the VSW is a challenge for any system. It was assumed that the mean time to detect and classify was 300 seconds with a standard deviation of 150 seconds using a lognormal distribution. When compared to a computer, it was assumed that the human would be much slower, and the variation would be much greater. The distribution was based on the task of classifying a mine being of unequal frequency and duration (Blanchard & Fabrycky, 2011). Informal top level discussions were held with Dr. Jake Wetzel (BCI Inc.), a subject matter expert in human systems integration working current with MCM issues. During these discussions it was discovered that the human would be considered better than a computer at reducing the false alarm rate of classifying non-mines as mines, but as this was not one of the metrics, this analysis was not continued (Wetzel, 2012). The rationale for this was that it would be better to have a false positive rather than a false negative. The addition of false positives would change the engagement function as another path may be chose through the minefield, or the mines to neutralize would be different depending on the detections.

In the same manner as Alternative One, a sensitivity analysis was performed using the model for Alternative Two. This consisted of using the same combinations of times and standard deviations as the analysis for Alternative One.

6. **Modeling Alternative Three**

The navigation system of this alternative consists of a Rate Gyro Compass with a DVL. The error in the rate gyro compass was assumed to be a normal distribution with a standard deviation of 1 degree (Boaters Land Discount Marine Supplies, 2011). The error in velocity was considered to be 1.9 cm/s based on the Teledyne RD Instruments Explorer PA technical specification (Teledyne RD instruments, 2011). The error for the direction was recalculated when the system changed direction and the error in the distance was calculated for each simulated movement.

Since this vehicle is in constant contact with the controlling platform, the alternative does not stop to communicate. Thus, times associated with communications were not factored in to the ACR.

The P_dP_c was set to 0.8. Since this system has the same sensor package as Alternative Two, and a human will be analyzing the data, the P_dP_c was kept the same.

Because the classification of the contacts will be performed the same way as Alternative Two, the time for this classification remained equal. However, since the vehicle would need to be recovered and have the data transferred to the personnel performing the analysis, an additional time was added to each contact. A delay equal to the time the vehicle took to search the minefield was added. This assumes that once the system has competed searching the minefield the PMA can begin. The PMA was estimated to take just as long as the in-mission analysis would take.

In the same manner as Alternative One, a sensitivity analysis was performed using the model for Alternative Three. This consisted of using the same combinations of times and standard deviations as the analysis for Alternative One.

7. Results for ACR and Undetected mines

Figure 68 depicts the ACR modeling results for each alternative in Minefield 1. Alternative One has a much greater ACR than the other two alternatives when performing a search in Minefield 1. Since the amount of time for each system to navigate the minefield was similar, this reflects that the difference in ACR is driven by the amount of time taken to perform detect and classification tasks.

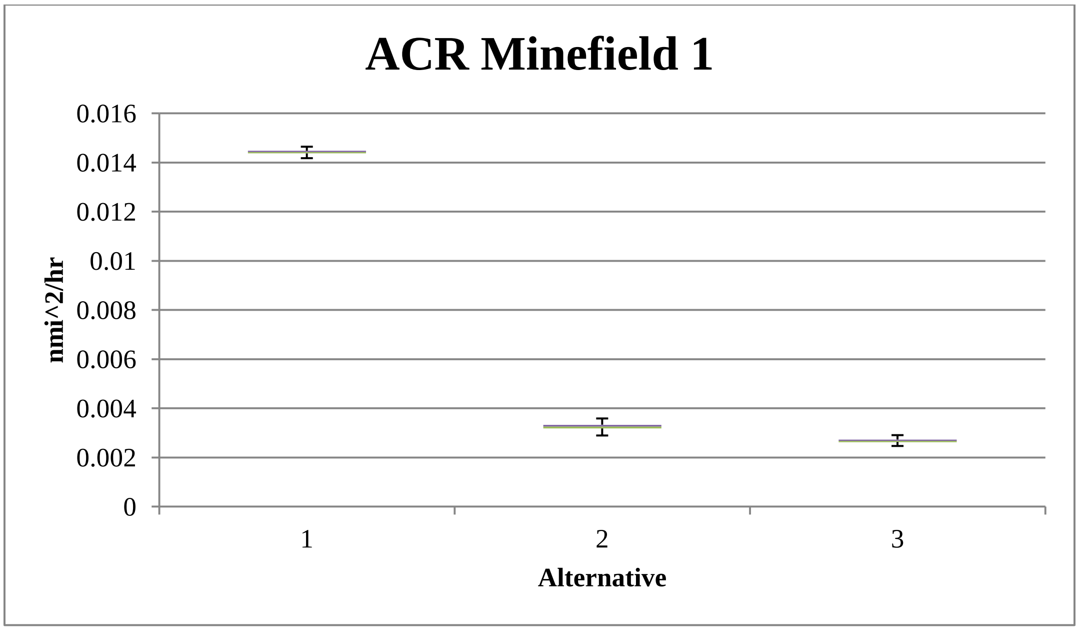

Figure 68. ACR Comparison of the Architectures in Minefield 1

This figure shows the ACR for each of the alternatives in Minefield 1. The units for the ACR are in square nautical miles per hour. The ACR was calculated using area searched divided by the time the architecture required to complete the area. The error bars on the box plots show the minimum and the maximum values calculated, the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

Figure 69 depicts the ACR modeling results for each alternative in Minefield 2. Since there were 100 fewer mines in Minefield 2, the ACR for each of the alternatives was better than that received in Minefield 1. Since Alternative One had the shortest detect and classify time, the difference is not as obvious as the other alternatives, but there is still a difference. This confirms the amount of time to perform detect and classify is the driving factor for ACR. A more detailed comparison of how the alternatives performed in the minefields can be seen in Appendix F.

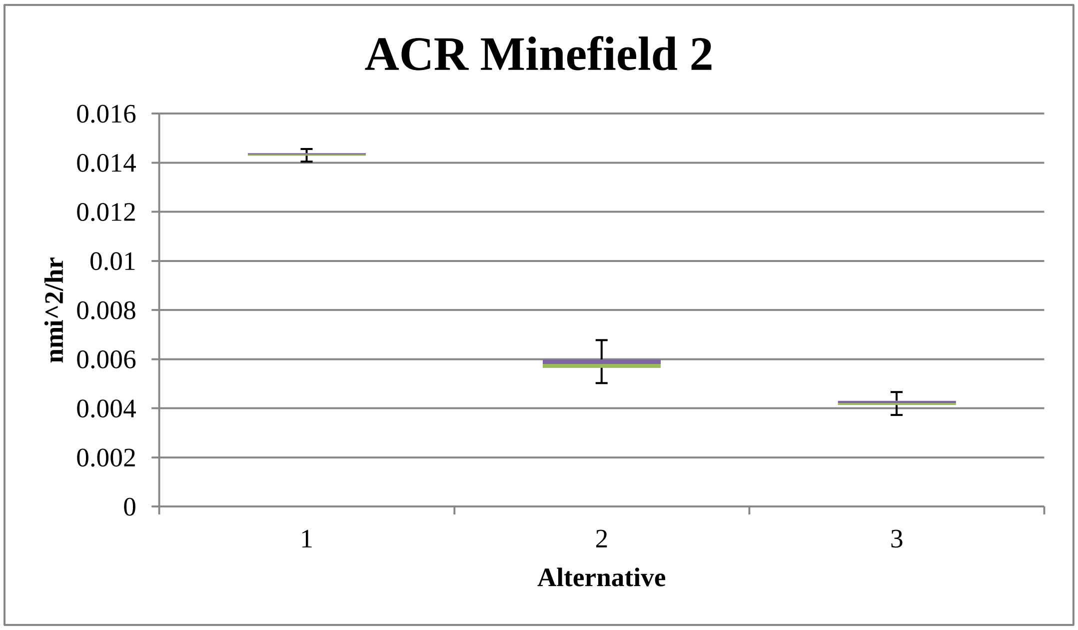

Figure 69. ACR Comparison for Minefield 2

This figure shows the ACR for each of the alternatives performed in the Minefield 2. The units for the ACR are in square nautical miles per hour. The ACR was calculated using area searched divided by the time the architecture required to complete the area. The error bars on the box plots show the minimum and the maximum values calculated, the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

In order to determine the effect of vehicle speed on the ACR, a sensitivity analysis was performed using ordered speeds of 3, 4, 5, & 6 knots. Figure 70 depicts this analysis and that unless the ordered speed is close to the water current's speed, there is limited statistically significant difference between the ordered speeds of the vehicle. Appendix F contains the detailed sensitivity analysis that was performed.

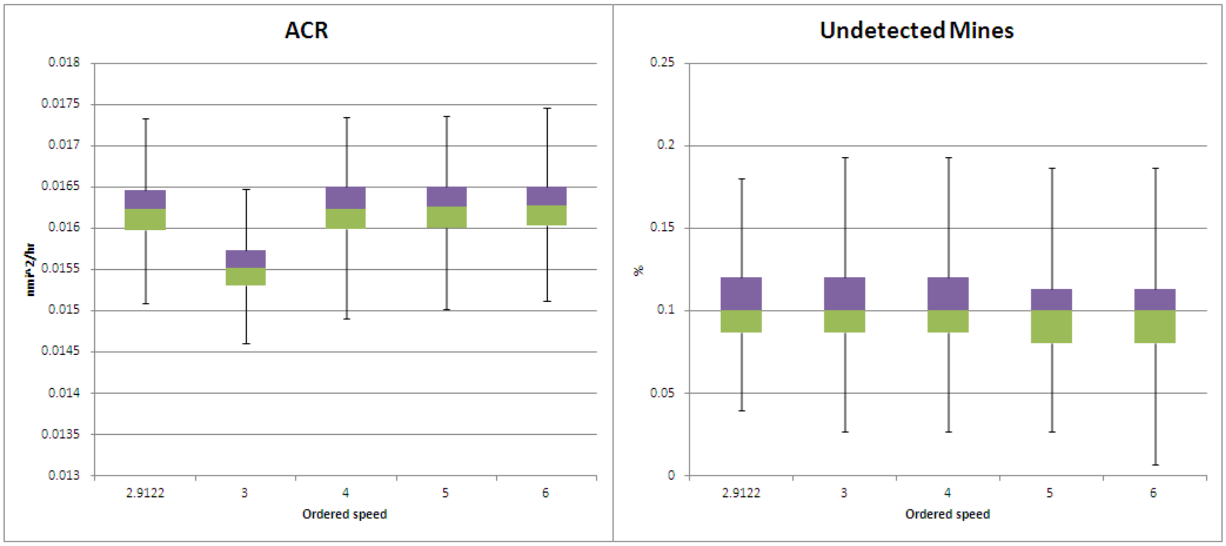

Figure 70. Speed Sensitivity analysis of Alternative One

This figure shows that for Architecture one the speed of the vehicle is not the limiting factor when it comes to the amount of time required to complete the minefield sweep. The error bars on the box plots show the minimum and the maximum values calculated, the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

A sensitivity analysis was performed on each of the three alternatives for the time to detect and classify, and the effect on ACR. Using mean times of 60 s, 120 s, and 240 s, and standard deviations of 20 s, 40 s, and 80 s, 1000 simulations of the three alternatives were performed for each combination of times and standard deviations. It was discovered that with a mean of 60 s with a standard deviation of 20 s, the ACR for all alternatives was statistically different. As either the standard deviation or the mean time was increased, the ACR for Alternative One and Alternative Two became statistically similar using the same mean and standard deviation. For all combinations of means and standard deviations, Alternative Three had a lower ACR. Figure 71 shows the results of the sensitivity analysis for the 60 s mean time for detect and classify. Additional information on the sensitivity analysis can be found in Appendix F.

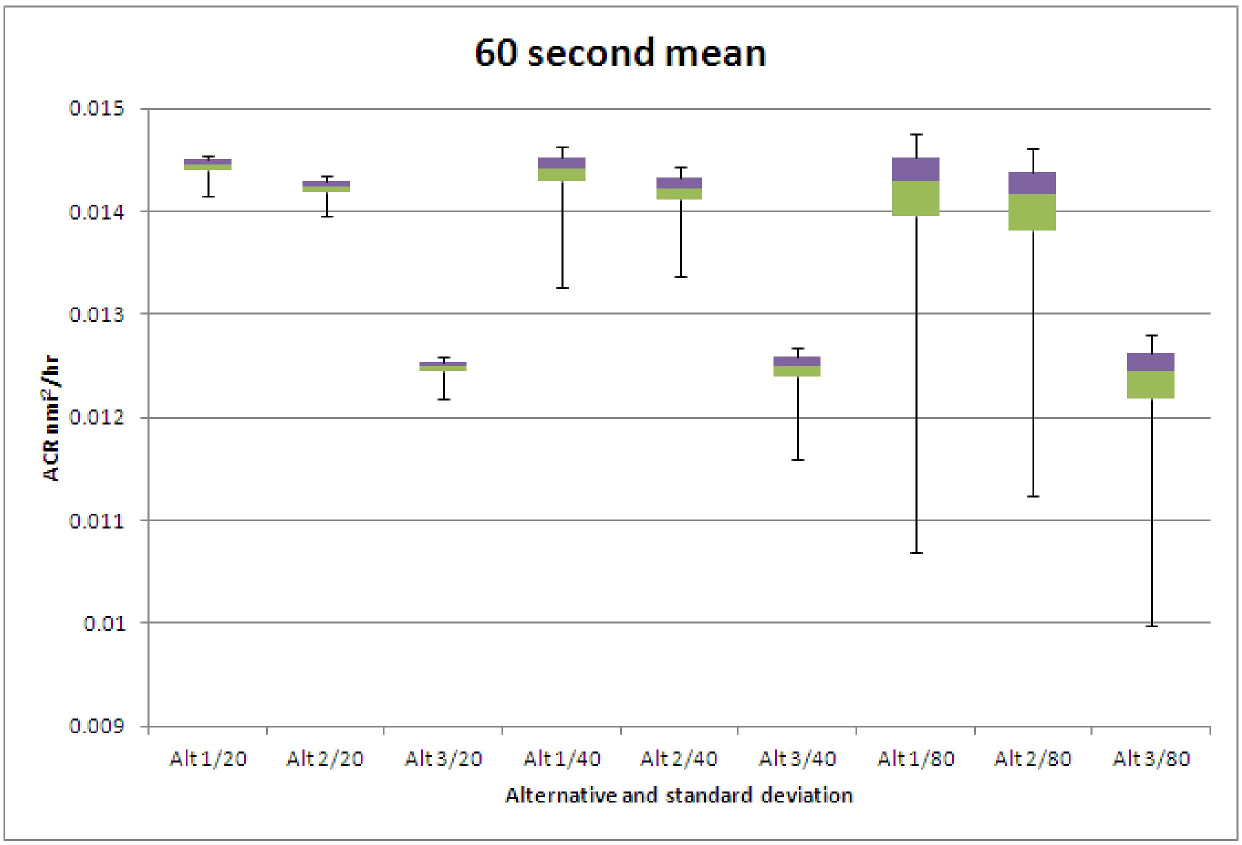

Figure 71. Sensitivity analysis for the alternatives using a mean of 60 seconds

This figure shows the results of the sensitivity analysis using a mean time of 60 seconds to detect and classify. The standard deviations used were 20 s, 40 s, and 80 s. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

For the metric of Undetected Mines, the analysis shows that Alternative One is statistically better than either of the other two alternatives. Figure 72 displays the results for the undetected mine metric for Minefield 1, and Figure 73 displays the results for the undetected mine metric for Minefield 2. The results of Alternative One and Alternative Two clearly show the difference in the P_dP_c. Although the difference between Alternative Two and Alternative Three is not statistically significant, it was demonstrated that when Alternative Three performed the search of the minefield, the error of the navigation caused a few mines to be outside of the sensor range.

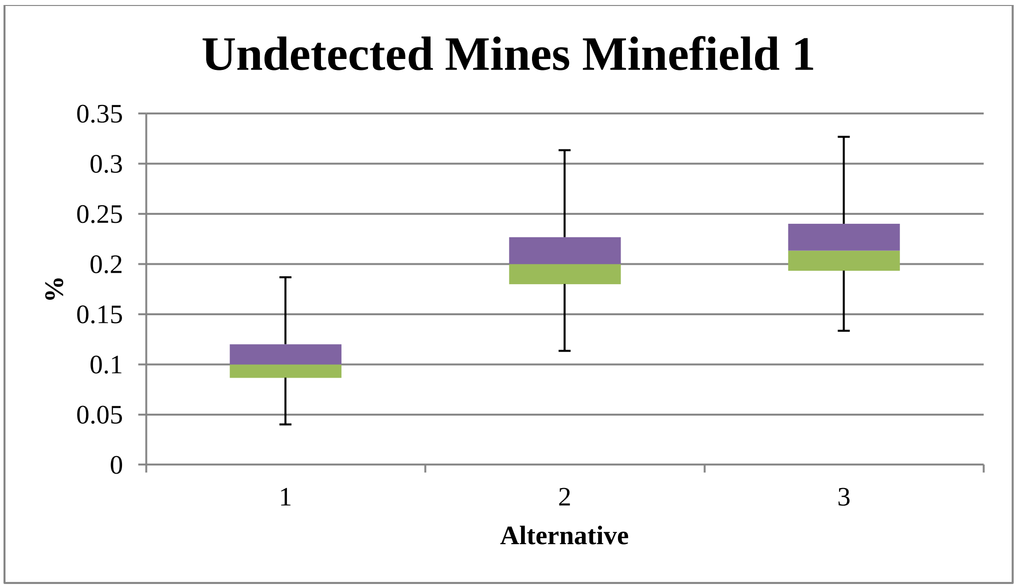

Figure 72. Undetected Mines in the Minefield 1.

This figure shows the percentage of undetected mines remaining after a single sweep of the minefield. This value is driven both by the P_dP_c and the error in navigation. The error bars on the box plots show the minimum and the maximum values calculated, the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

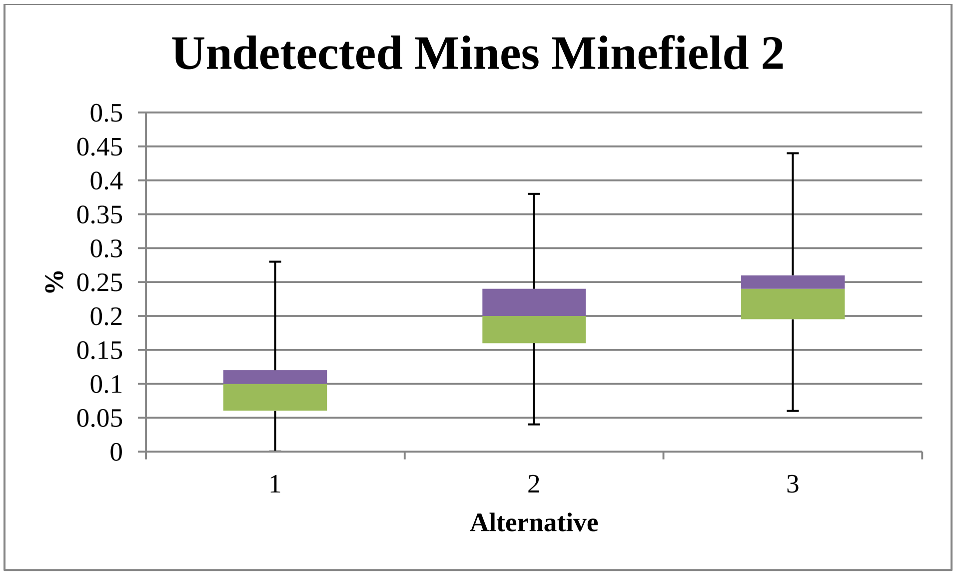

Figure 73. Undetected Mines in the Minefield 2.

This figure shows the percentage of undetected mines remaining after a single sweep of the minefield. This value is driven both by the P_dP_c and the error in navigation. The error bars on the box plots show the minimum and the maximum values calculated, the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

E. NUMBER OF SYSTEMS NEEDED

The requirements analysis found that the threshold ACR of the system needs to be 0.083 n.m.^{2}/hr, with an objective of 0.125 n.m.^{2}/hr. These values were determined by taking the entire possible area of coverage divided by the amount of time that would be available to search before an amphibious assault. The results for the simulated ACR, for all architectures, were determined for one vehicle in the 500 yard by 500 yard test area. The difference between the requirements and the simulated results found that one vehicle would not be able to complete the entire mission in the required time.

In order to determine the number of systems required to achieve the capability for the entire mission, the required ACR was divided by the alternative's minimum modeled ACR. These values were rounded up and can found in Table 23. From this calculation, it was determined that 6 systems were needed for Alternative One, 29 systems for Alternative Two, and 34 systems for Alternative Three. With the wide variety in the required number of vehicles, a decision needed to be made as to which values would be used for further analysis. The basis of this decision was that the threshold was the minimum required value for a system to be deemed acceptable.

Table 23. Number of Vehicles Need to Achieve Capability

This table shows the number of vehicles needed in the search area in order to achieve the threshold of 0.083 n.m.^{2}/hr and objective of 0.125 n.m.^{2}/hr. Vehicles highlighted are accepted as assumptions for further analysis in this report.

	Alternative 1	Alternative 2	Alternative 3
Minefield 1			
Number of vehicles needed to reach Threshold	6	29	34
Number of vehicles needed to reach Objective	9	44	51
Minefield 2			
Number of vehicles needed to reach Threshold	6	17	23
Number of vehicles needed to reach Objective	9	25	34

The performance of a vehicle in Minefield 2 was found to be better than in Minefield 1. If the performance of the system could achieve the required threshold for Minefield 1, it would follow that for Minefield 2 the performance would exceed the required threshold. In order to ensure that 99% of all searches were capable of meeting the threshold, the minimum ACR value from Minefield 1 was selected as the value to compare to the requirement threshold. This was because the ACR data had a normal distribution with the minimum being within two standard deviations from the mean. Without improvements to the vehicle performance, the only way to

reach the objective was to use additional vehicles which would not only increase the total overall system cost, but have a negative effect on the total logistical footprint of the system.

VI. LIFE CYCLE COST ESTIMATE

A life-cycle cost estimate (LCCE) for each alternative was prepared in order to analyze the total cost for acquisition and ownership of the MCM system over its useful life. This life-cycle cost (LCC) includes the cost of research and development, testing, acquisition, production, facilities, operations, maintenance, personnel, environmental compliance, sustainment, and disposal.

These LCC costs for each MCM system alternative are subtotaled in the following lifecycle phases: research and development (R&D), investment, operating and support (O&S), and disposal.

I. R&D: This category includes the cost of all research and development, from program initiation through the Full Rate Production (FRP) decision.

II. Investment: The total cost of the investment phase is included in this category. It includes total cost of procuring the prime equipment, related support equipment, training, initial and war reserve spares, pre-planned product improvements and military construction.

III. O&S: The bulk of life-cycle costs occur during this category, which covers the cost of operating and supporting the fielded system. O&S includes all direct and indirect costs incurred in using the system, e.g., personnel, maintenance, and sustaining investment (replenishment spares).

IV. Disposal: This category includes all costs related to disposing of the MCM system at the conclusion of its useful life. It includes demilitarization, detoxification, long-term waste storage, environmental restoration and related costs.

A. APPROACH

The LCCE was initiated utilizing recommended research provided by RDML Richard Williams, USN (RET). His recommendation included utilizing the LCCE Breakdown Structure out of Chapter 17 in Blanchard and Fabrycky, Systems Engineering and Analysis, Fifth Edition (Blanchard & Fabrycky, 2011). This provided a Cost Breakdown Structure (CBS) enabling cost analysis down to the subcategory level.

In order to begin the LCCE process, we began by assuming the MCM program was currently in the materiel solution analysis (MSA) systems engineering phase in accordance with the Integrated Defense Acquisition, Technology, and Life Cycle Management System. During this phase, the analysis of alternatives was completed to assess potential materiel solutions to the capability need, identify key technologies and estimate life cycle costs. Continuing to follow the DoD Life Cycle Management System, the research, development, test and evaluation (RDT&E) funding was used to support development efforts throughout the system lifecycle from advanced

technology development, lasting through Milestone (MS) A decision; advanced component development and prototypes, lasting from the MS A decision through the MS B decision; the systems development and demonstration, from the MS B decision through the MS C decision; and management support, lasting through FRP.

Next, the procurement (PROC) funding was used to finance investment items and should cover all costs integral and necessary to deliver a useful end item intended for operational use or inventory. This funding would be used from the MS C decision through FRP or deployment.

The operations and maintenance (O&M) funding was used to finance things that derive benefits for a limited period of time, including expenses, rather than investments. O&M funding would be used from FRP through disposal. Some examples include: headquarters operations, civilian salaries, travel, fuel, expenses of operational military forces, training and education, depot maintenance, and base operations support.

The R&D cost category utilized available RDT&E funding. Likewise, the investment cost category, (which were noted as acquisition, production and construction), utilized available PROC funding. The O&S and disposal cost categories utilized available O&M funding.

The MCM program is currently nearing completion of the systems engineering MSA phase. It is anticipated that it will take an additional six months before a MS A decision is reached. This program will take one year to complete the systems engineering technology development phase and obtain a MS B decision. The engineering and manufacturing development systems engineering phase will take a total of approximately 2.5 years before a MS C decision is reached. The System Integrated Design will take approximately one year; followed by the system capability & manufacturing process demonstration, which will take another 1.5 years to complete. It is anticipated that the duration of the production and deployment phase will be 5 years total: two years to complete low rate initial production (LRIP) and three years to reach a full-rate production (FRP) and deployment decision. The O&S phase will last approximately 12 years. Life cycle sustainment will last approximately 8 years followed by 4 years for system disposal. The overall MCM system life-cycle is estimate to conclude in 20 years based off information from the MK 18 LCCE (Tecolote Research, Inc., 2008).

Continuing the Life Cycle Cost Analysis, the CBS was developed. The ROM life-cycle cost estimate was generated by referencing the MK18 UUV service based contracts estimation related reports (Tecolote Research, Inc., 2008; PMS 408, 2011). The cost information from the MK18 was obtained from multiple sources, including service contracts, subject matter experts (SME), and limited available reference documentation.

Technical skill and ability for this project has been estimated at a GS-13 level for all labor categories throughout this project including, but not limited to the project manager, software engineer, and technicians throughout the lifecycle. The average labor rate was estimated at $200K per man year, based upon loaded rates for NAVSEA in the Newport area (Castonguay, 2011). The labor throughout the LCCE was adjusted to include an estimated 4% annual inflation rate based on predicted six year inflation up trend (McMahon, 2012).

The material costs were estimated using a combination of quotes, open literature vendor data, GSA schedule database like IHS Haystack (IHS Inc., 2012), and PMS 408 (EOD) program office. The majority of required materials were identified for cost estimation, however not all materials for a complete system were identified. In addition to the materials, the facility costs were based off a $10 per square foot estimate. The total cost for facilities was based on the total estimated area required for each system. The material and facility costs throughout the LCCE were also adjusted to include the estimated 4% annual inflation rate (McMahon, 2012).

B. ALTERNATIVE ARCHITECTURE COSTS

This section presents the estimated costs over the projected life-cycle of each alternative. These life-cycle costs were used in order to perform a cost analysis and determine the preferred alternative. A bottom-up cost estimate was conducted for each alternative with a modular approach accounting for the MCM vehicle, control station, and support equipment/facilities to arrive at a total MCM system cost. A detailed costs breakdown for each alternative can be found in Appendix G.

1. Alternative One Costs

The LCCE analysis for this alternative was based on a system consisting of six vehicles to meet the threshold requirements for a worst case scenario (minefield 1) as shown in Table 23. The estimated total cost for Alternative One was calculated at $100.45M. The following paragraphs detail the overall cost for each phase of the system lifecycle.

a. R&D Costs

The R&D phase is four years (FY-1 through FY-4). The total cost estimation for this phase is $39.49M as shown in Table 24. The R&D phase was broken into six categories to determine the R&D costs: System/Production, Product Planning, Product Research, Engineering Design, Design Documentation, and System T&E. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 24 are summations of each its subcategories.

Table 24. Summary of Alternative One R&D Costs

Summary of the MCM Alternative One R&D costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

R&D Category	Cost
System/Production	$1.83M
Product Planning	$0.21M
Product Research	$0.89M
Engineering Design	$23.38M
Design Documentation	$0.87M
System T&E	$12.31M
Total	**$39.49M**

System/Production costs included paying a Project Manager for FY 1-4 one man year (MY) each year, a Production Manager for FY 3-4 one MY each year, a Logistics Support Manager for FY 1-2 one quarter MY each year, and a Logistics Support Manager for FY 3-4 one MY each year. Each of these managers were estimated at an average rate of $200K, plus an inflation rate of 4% for each year past FY 1. The Project Manager would be required from the onset of the project. The Production Manager was deemed necessary once the designs had taken shape and requirements started. The Logistics Support Manager would be need part-time from day 1 and would ramp up to full-time starting in year three for the same reasons the Project Manager is needed at that same time.

The main factor of cost in R&D was the Engineering Design. Engineering Design was broken up into several phases/categories: Systems Engineering, Conceptual Design, Preliminary Design, Detailed Design, Design Support, Design Review, and Software Engineering. The $200K average work-year rate was also utilized for all of the personnel working these phases. In FY 1&2, a System Engineer would be used to help arrange the design efforts and work with the Project Manger to develop the plan for design phase. The Conceptual Design was performed in FY 1&2 by two designers. The Preliminary Design was estimated to be performed in FY 2&3 by two different designers. The Detailed Design was planned in FY 3&4 by another set of designers. Design Support was also estimated to be required in FY 3&4. Design Reviews were scheduled to occur in FY 2, 3, and 4. During FY 4, the Preliminary Design Review (PDR) and Critical Design Review (CDR) were estimated to take place, which resulted in an increase of cost incurred during FY4 when compared to other years. The Software Engineering was the largest single cost factor for the Alternative One R&D phase. The amount of the lines of code was

considerably larger for this design than what would be needed for the other two alternatives due to the large amount of internal processing required.

b. Investment (Acquisition/Production/Construction) Costs

The total cost estimation for the investment phase was found to be $26.04M as shown in Table 25. The Investments phase is five years (FY-5 through FY-9) long and was broken into the following five categories to determine the respective investment costs: Industrial Engineering, Manufacturing, Construction, Quality Control, and Initial Logistics Support. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 25 are summations of each its subcategories.

Table 25. Summary of Alternative One Investment Costs

Summary of the MCM Alternative One investment costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

Investment Category	Cost
Industrial Engineering	$9.50M
Manufacturing	$11.89M
Construction	$2.85M
Quality Control	$0.76M
Initial Logistics Support	$1.04M
Total	**$26.04M**

Industrial Engineering and Manufacturing were the largest two contributors to the Investment Costs. The Industrial Engineering Costs were broken out into Plant Engineering, Manufacturing Engineering, Methods Engineering, Production Control, and Sustaining Engineering. For each of the alternatives, the original values were based upon one supporting person working each phase. It was determined later that Alternative One would be more expensive due to the additional requirements of implementing the software during the integration period.

The Manufacturing Costs were comprised of the Tooling/Test Equipment, Fabrication, Material, Subassembly/Assembly, Inspection & Test, Packing & Shipping, and Manufacturing Rework. The values for each of these sections were based upon previous manufacturing experience from members of the cohort. The material was the only line item that was based upon the actual material costs and quantity of assemblies required to make one complete system (Alternative One = 6, Alternative Two = 29, and Alternative Three = 34).

c. *Operating & Support Costs*

The total cost estimation for the Operating and Support phase is $30.57M and is broken out in Table 26. The O&S phase is eight years long (FY-10 through FY-17) and was broken into the following categories: System/Product and Sustaining Costs. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 26 are summations of each its subcategories.

Table 26. Summary of Alternative One O&S Costs

Summary of the MCM Alternative One O&S costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

O&S Category	Cost
System/Product	$5.59M
Sustaining	$24.99M
Total	**$30.57M**

The System/Product costs were broken out into Operating Personnel, Operator Training, Operational Facilities, and System Maintainer categories. The costs per person per year for this section were $100K. The Operator Training was estimated at $5K (for roughly two weeks per year) per person. The facility requirements (i.e. production, storage, etc) for Alternative One were estimated at 5000 sq. ft. and averaging $10 per sq. ft. per year (National Reality, 2012). These were both based upon average costs of renting facilities and the area needed was based upon previous area requirements of systems built and operated by members of the cohort. For Alternatives Two and Three, the amount of area was doubled due to the larger number of the components needed. The amount of area needed was not based solely on sq. ft per system, but also additional factors such as required support personnel to work in the facility to support each alternative.

d. *Disposal Costs*

The total cost estimation for the Disposal phase is $4.34M. The disposal will consist of the following categories: logistics support requirements, equipment support, transportation & handling support, facilities during a four year period, from FY-18 through FY-21.

The Disposal costs were based upon the need of one person to perform logistics support requirements full time for four years. An additional person would be needed for personnel support. Each of these personnel would be paid the $200K average yearly rate. Since these values are 18 years out, the 4% inflation rate assumed each year almost doubles their current dollar equivalent. The equipment support and transportation/handling support costs were based

upon current shipping costs and equipment rental. Values were obtained from cohort member experience. The Facility requirements were based on 5000 sq. ft. at $10 per sq. ft. per year.

The remaining Alternative Two and Three costs were determined by the above mentioned methods. Variations between some of the alternative costs have been discussed previously. Major differences in costs have been primarily attributed to quantities of people required (example: Alternative Two requires 29 vehicles with 6 people supporting every two vehicles and Alternative Three requires 34 vehicles with 8 people supporting every two vehicles) amount of work needed to perform the action (example: Software Engineering in Alternative One).

2. Alternative Two Costs

The LCCE analysis for this alternative was based on a system consisting of twenty-nine vehicles to meet the threshold requirements for a worst case scenario (minefield 1) as shown in Table 23. The performance of a vehicle in Minefield 2 was found to be better than in Minefield 1. If the performance of the system could achieve the required threshold for Minefield 1, it would follow that for Minefield 2 the performance would exceed the required threshold. In order to ensure that 99% of all searches were capable of meeting the threshold, the minimum ACR value from Minefield 1 was selected as the value to compare to the requirement threshold. This was because the ACR data had a normal distribution with the minimum being within two standard deviations from the mean. Without improvements to the vehicle performance, the only way to reach the objective was to use additional vehicles which would not only increase the total overall system cost, but have a negative effect on the total logistical footprint of the system.

The estimated total cost for Alternative Two was calculated to be $285.08M. The following sections detail the overall cost for each phase of the system lifecycle.

a. R&D Costs

The R&D phase is four years long (FY-1 through FY-4) and is estimation to cost $24.96M as shown in Table 27. The R&D phase was broken into six categories to determine the R&D costs: System/Production, Product Planning, Product Research, Engineering Design, Design Documentation, and System T&E. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 27 are summations of each its subcategories.

Table 27. Summary of Alternative Two R&D Costs

Summary of the MCM Alternative Two R&D costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

R&D Category	Cost
System/Production	$1.83M
Product Planning	$0.21M
Product Research	$0.89M
Engineering Design	$11.23M
Design Documentation	$0.87M
System T&E	$9.93M
Total	**$24.96M**

b. Investment (Acquisition/Production/Construction) Costs

The total cost estimation for the Investments phase is $50.20M as seen in Table 28. The Investments phase is five years (FY-5 through FY-9) long and was broken into the following five categories to determine the respective investment costs: Industrial Engineering, Manufacturing, Construction, Quality Control, and Initial Logistics Support. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 28 are summations of each its subcategories.

Table 28. Summary of Alternative Two Investment Costs

Summary of the MCM Alternative Two investment costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

Investment Category	Cost
Industrial Engineering	$6.34M
Manufacturing	$31.40M
Construction	$5.30M
Quality Control	$3.02M
Initial Logistics Support	$4.15M
Total	**$50.20M**

c. Operating & Support Costs

The total cost estimation for the Operating and Support phase is estimated at $204.54M and is detailed in Table 29. The O&S phase is eight years long (FY-10 through FY-17) and was broken into the following categories: System/Product and Sustaining Costs. Each of these categories was also broken down into subcategories. The breakout of these categories into

subcategories can be found in Appendix G. The values shown in Table 29 are summations of each its subcategories.

Table 29. Summary of Alternative Two O&S Costs

Summary of the MCM Alternative Two O&S costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

O&S Category	Cost
System/Product	$135.74M
Sustaining	$68.80M
Total	**$204.54M**

d. Disposal Costs

The total cost estimation for the Disposal phase is $5.38M. The disposal will consist of the following categories: logistics support requirements, equipment support, transportation & handling support, facilities during a four year period, from FY-18 through FY-21.

3. Alternative Three Costs

The LCCE analysis for Alternative Three is based one system consisting of thirty-four to meet the threshold requirements for a worst case scenario (minefield 1) as shown in Table 23. The estimated total cost for Alternative Three was estimated to be $326.33M. The following paragraphs detail the overall cost provided for each phase of the system lifecycle.

a. R&D Costs

The R&D phase is four years long (FY-1 through FY-4) and the total cost is estimated to be $23.97M, shown in Table 30. The R&D phase was broken into six categories to determine the R&D costs: System/Production, Product Planning, Product Research, Engineering Design, Design Documentation, and System T&E. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 30 are summations of each its subcategories.

Table 30. Summary of Alternative Three R&D Costs

Summary of the MCM Alternative Three R&D costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

R&D Category	Cost
System/Production	$1.83M
Product Planning	$0.21M
Product Research	$0.89M
Engineering Design	$11.23M
Design Documentation	$8.94M
System T&E	$4.84M
Total	**$23.97M**

b. Investment (Acquisition/Production/Construction) Costs

The total cost estimation for this phase is $41.48M shown in Table 31. The Investments phase is five years (FY-5 through FY-9) long and was broken into the following five categories to determine the respective investment costs: Industrial Engineering, Manufacturing, Construction, Quality Control, and Initial Logistics Support. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 31 are summations of each its subcategories.

Table 31. Summary of Alternative Three Investment Costs

Summary of the MCM Alternative Three investment costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

Investment Category	Cost
Industrial Engineering	$6.34M
Manufacturing	$22.67M
Construction	$5.30M
Quality Control	$3.02M
Initial Logistics Support	$4.15M
Total	**$41.48M**

c. Operating & Support Costs

The total cost estimation for this phase is $255.50M illustrated in Table 32. The O&S phase is eight years long (FY-10 through FY-17) and was broken into the following categories: System/Product and Sustaining Costs. Each of these categories was also broken down into subcategories. The breakout of these categories into subcategories can be found in Appendix G. The values shown in Table 32 are summations of each its subcategories.

Table 32. Summary of Alternative Three O&S Costs

Summary of the MCM Alternative Three O&S costs. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

O&S Category	Cost
System/Product	$201.70M
Sustaining	$53.80M
Total	**$255.50M**

d. Disposal Costs

The total cost estimation for this phase is $5.38M. The disposal will consist of the following categories: logistics support requirements, equipment support, transportation & handling support, facilities during a four year period, from FY-18 through FY-21.

C. LCCE COMPARISON

The analysis of the cost is based on the LCCE for each alternative. The key drivers impacting the overall cost are analyzed by life-cycle phase. The total costs for each alternative are presented in Table 33 and illustrated in a stacked bar in Figure 74.

Table 33. Life Cycle Cost Estimation Summary for each Alternative

Summary of the overall total costs for each MCM alternative broken down by R&D, investment, O&S and disposal for each. The table was compiled from the LCCE spreadsheets generated using multiple sources for cost estimation.

	ALTERNATIVE ONE	ALTERNATIVE TWO	ALTERNATIVE THREE
R&D	$39.49M	$24.96M	$23.97M
Investment	$26.04M	$50.20M	$41.48M
O&S	$30.57M	$204.54M	$255.50M
Disposal	$4.34M	$5.38M	$5.38M
TOTAL	**$100.45M**	**$285.08M**	**$326.33M**

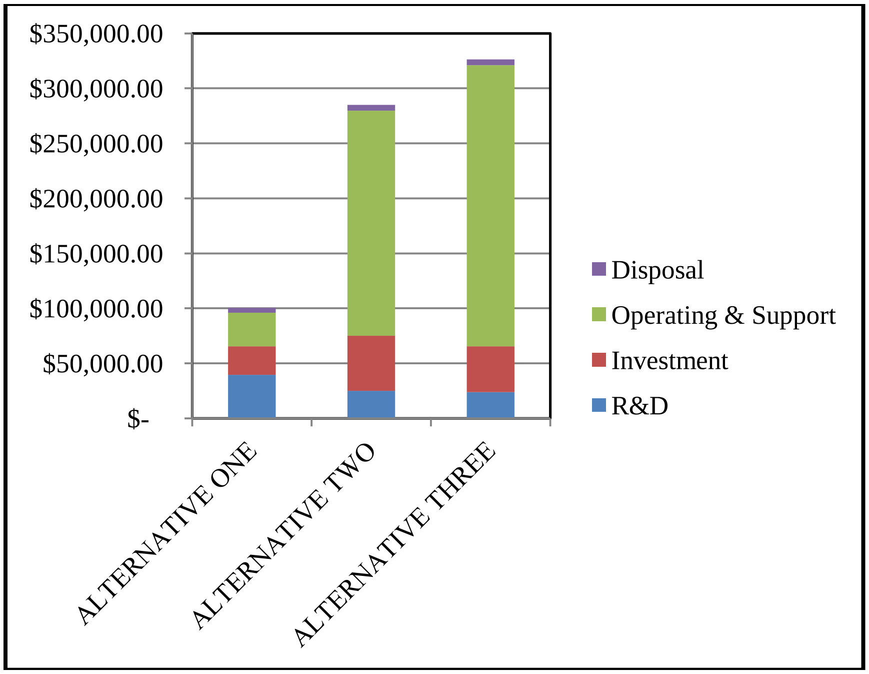

Figure 74. Total Stacked LCCE Costs for MCM Alternatives

The overall total costs (shown in $K) for each MCM alternative are compared, stacking R&D, investment, O&S and disposal for each. The total cost for each alternative is: $100,450K (Alternative One), $285,080K (Alternative Two), and $326,330K (Alternative Three). The largest impact on total cost for Alternatives Two and Three is noted during the O&S phase. The largest impact on total cost for Alternative One is during the R&D phase.

1. R&D Cost Comparison

The labor impacted the total cost between each alternative with the most significant labor driver in design and building the prototypes. The design labor required to create the software for Alternative One was approximately three times as expensive as the other two alternatives. The amount of processing required for this fully autonomous alternative requires more lines of code, thus more software engineers are needed as commuted by COCOMO II web-based software estimation tool (Madachy, 2012). The other two alternatives will have more operational personnel working with the systems and will require less processing/less lines of code. The major differences in building prototypes are the number of vehicles required to build. In Alternative One, six vehicles are required, twenty-nine are required for Alternative Two, and thirty-four are needed for Alternative Three. In addition to labor, materials significantly impacted the total cost. In summary, the R&D costs for Alternative One, Two, and Three are, respectively: $39.49M, $24.96M, and $23.97M. The Alternative One R&D cost is approximately $15M and $16M higher than Alternatives Two and Three, respectively. As stated

above, this is mainly due to the increased software labor needs and the system complexity of Alternative One's fully autonomous requirements.

2. Investment (Acquisition/Production/Construction) Cost Comparison

The major driver between alternatives is the quantities of vehicles per system affecting the construction and production costs. Other major costs included in each alternative are the facility, area, and material. In summary, the total investment costs for Alternative One, Two, and Three are, respectively: $26.04M, $50.20M, and $41.48M. The cost per vehicle for each alternative are: Alternative One = $4.34M/vehicle ($26.04M/6 vehicles), Alternative Two = $1.73M/vehicle ($50.20M/29 vehicles), and Alternative Three = $1.22M/vehicle ($41.48M/34 vehicles). Even though the price per vehicle is more for the Alternative One, the quantity of vehicles needed is only six and this results in a total cost considerably less than the Alternatives Two and Three. The Alternative Two investment costs are just short of $9M higher than Alternative Three, and just over $24M more than Alternative One. Although, the Alternative Two number of systems is lower than Alternative Three, the materials costs per system are higher.

3. O&S Cost Comparison

The most significant impact to alternative costs is the number of operators and maintainers required. In order to support the number of vehicles (Alternative One = 6, Alternative Two = 29, and Alternative Three = 34) and keep each alternative system fully operational, functional, and continuously supported, the following number of personnel are required: Alternative One = 12 operators (2 operators per vehicle 6 vehicles) and 2 maintainers total; Alternative Two = 87 operators (3 operators per vehicle 29 vehicles) and 8 maintainers total; and Alternative Three = 136 operators (4 operators per vehicle 34 vehicles) and 10 maintainers total. In summary, the O&S costs for Alternative One, Two, and Three are, respectively: $30.57M, $204.54M, and $255.50M. The Alternative Three O&S costs are approximately $51M higher than Alternative Two, and nearly $225M more than Alternative One.

4. Disposal Cost Comparison

The significant impacts to cost are the transportation and facility requirements for each alternative. In summary, the disposal costs for each alternative are: $4.34M, $5.38M and $5.38M. The disposal costs for Alternative Two and three are nearly $1M more than Alternative One mainly due to the total number of vehicles in the fleet.

D. LCCE RESULTS

Based on the cost comparison, Alternative One provides the lowest lifecycle costs as compared to Alternatives Two and Three. The difference in total costs between Alternative One and Two is just under $185M. The difference between Alternative One and Three is approximately $226M.

Figure 74 illustrates that the 8 year O&S life-cycle phase is the largest driver of cost for Alternatives Two and Three and the 4 year R&D life-cycle phase impacts cost the most for Alternative One. If longer sustainment is necessary, then Alternative One would have a substantial cost benefit over the other alternatives based on the LCCE performed.

The final key variable to cost is the number of vehicles required per system in each alternative to support the mission. The material and facilities costs are major cost impacts due to the number of required vehicles for alternative systems. Because Alternative One requires fewer vehicles in its system configuration, it will have a lower cost related to materials and facilities.

VII. ANALYSIS OF ALTERNATIVES

A. BENEFIT ANALYSIS

To complete the overall assessment of each alternative, a benefit analysis was performed to compare the effectiveness and lifecycle cost factors. The objective of the analysis was to select the best recommended system by examining all the factors to understand what alternatives have the most benefits and the least amount of detractors.

1. Effectiveness Evaluation

The effectiveness analysis was conducted on the three Measures of Effectiveness (MOEs) of ACR, stealth, and undetected mines. Since the model was based on one vehicle for each of the alternatives to calculate the MOEs, the evaluation of the number of vehicles will have to be applied to each alternative to get a whole system to whole system comparison. The assessment considers the total number of MCM vehicles required for each alternative system.

The Alternative One architecture achieved the best performance scores for the MOEs over the other architectures in modeling and simulation. Alternative Two received the second best score, while Alternative Three showed the lowest scores in all three MOE categories. Table 34 summarizes the rank-ordered scores for each alternative in the effectiveness analysis.

Table 34. Rank-Ordered Scores of Alternatives

This table shows the rank-ordered scores of the alternative systems for each MOE assessed. A score of 1 is the best while a score of 3 is the worst.

Measure of Effectiveness (MOE)	Data Type	Alternative		
		One	Two	Three
Area coverage Rate (n.m.^{2}/hr) Rank	Test	1	2	3
Stealth (%) Rank	Observed	1	2	3
Undetected Mines (%) Rank	Test	1	2	3

Modeling and simulation also calculated the number of vehicles required to meet the mission need for each alternative. While the number of vehicles for each system increased, it did not affect the performance ranking of the systems. This is due to the fact that the number of vehicles increased more for the lower ranked alternatives. It is understood that while the metrics of ACR, stealth, and undetected mines may change due to the addition of more vehicles to cover the entire mine field in the required time frame, the resulting effect is that the gaps between the systems' performance will only increase. Based on the number of required vehicles for each

alternative, it was determined that there is no impact on the rank-ordering of alternatives presented in Table 34.

2. Cost Evaluation

Cost is a major factor in the decision for selecting the best alternative from the three alternatives. Table 35 summarizes the total Life Cycle Cost estimate of each alternative taking into account the number of vehicles required at the system level.

Table 35. Life Cycle Cost Estimation Summary for Each Alternative

This table shows the overall lifecycle cost per phase for each alternative.

Lifecycle Phase	Alternative		
	One	**Two**	**Three**
R&D	$39.49M	$24.96M	$23.97M
Investment	$26.04M	$50.20M	$41.48M
O&S	$30.57M	$204.54M	$255.50M
Disposal	$4.34M	$5.38M	$5.38M
TOTAL	**$100.45M**	**$285.08M**	**$326.33M**

It is evident from Table 35 that Alternative One is overall the least costly system, followed by Alternative Two and Alternative Three as the most costly.

3. Benefit Analysis Process

In an attempt to determine which alternative was comparatively the better choice, a benefit analysis was performed to compare each system's cost and performance. This evaluation shows which alternative results in the best combination of cost and effectiveness.

Figure 75 displays each of these alternatives with their overall performance and total cost. Alternative One has the lowest cost and with the highest score for each MOE. Alternative Two has the second best cost and performance scores while Alternative Three was the worst performing system with the highest cost. Therefore Alternative One possesses the highest performance of the three alternatives as well as the lowest Life Cycle Cost and is our best selection from the alternatives evaluated.

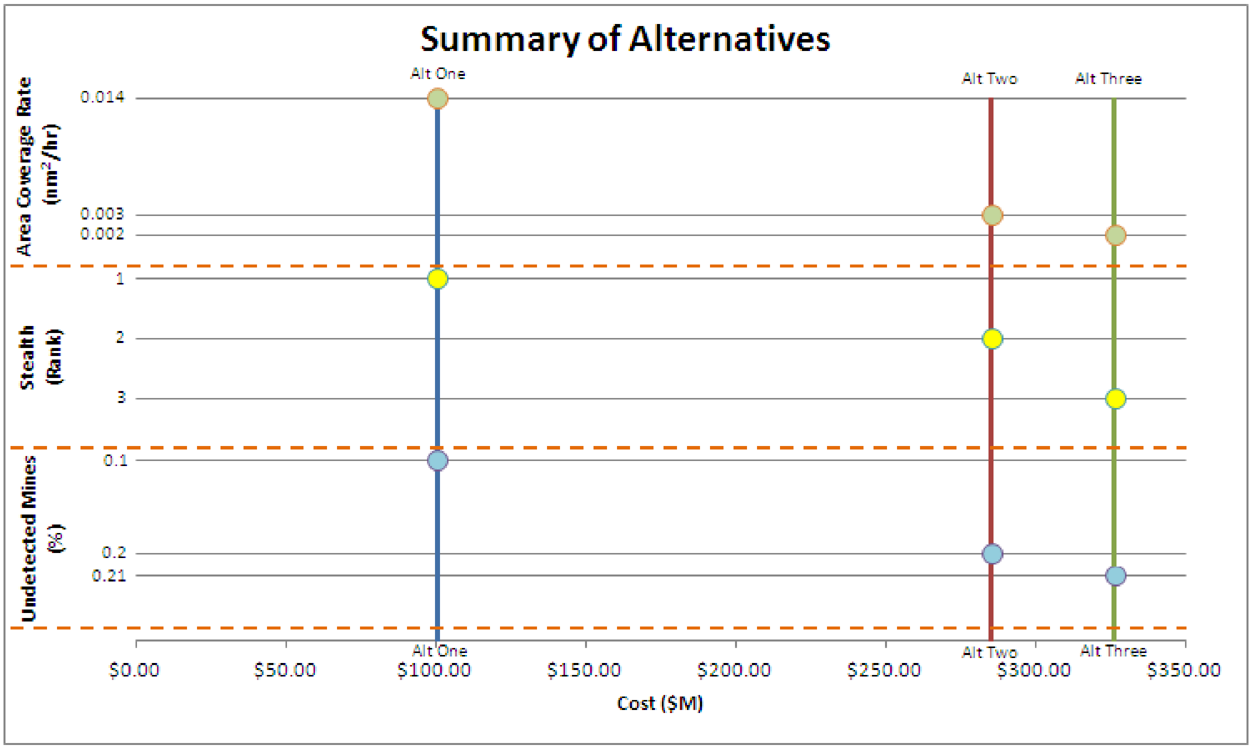

Figure 75. Decision evaluation chart

The total lifecycle costs (shown in $M) and overall performance for each MCM alternative are displayed to aid in the comparative analysis for making a best selection. The dashed lines separate the MOEs evaluated for each of the alternatives allowing the comparison to remain on one chart.

B. BENEFIT ANALYSIS SUMMARY

To provide a final system recommendation, a benefit analysis was conducted based on the analysis of the performance and cost of the alternatives. Alternative One has a much higher R&D phase cost than the other alternatives shown in Table 35, but due to its considerably lower O&S costs it remains as the lowest cost option. Based on cost it was still the most favorable choice when compared to Alternatives Two and Three. If the O&S phase was shorter than 8 years, Alternative One would not be the lowest cost; however the O&S duration is considered conservative and less than 8 years is not a reasonable estimation. Since the results for both the effectiveness and lifecycle cost analyses had the same top candidate, the benefit analysis confirmed that Alternative One was the best selection providing the most affordable system with the best operational effectiveness.

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VIII. CONCLUSION

A. FINDINGS

The comparison of Alternative One, Two and Three displayed the benefit of each of the recommended capability gap solutions. The overall system recommendation, Alternative One, was a system that included fully autonomous capabilities, onboard real-time data fusion and processing, and a real-time communications network with an OTH capability. The other alternatives were found to be able to the complete MCM mission, but did not always meet developed stakeholder requirements. For example, Alternative Two did provide a reduction of DTE time by using a real-time communications network, but the burden of identifying, classifying and processing targets was still placed upon human operators requiring increased manpower support compared to Alternative One. Alternative Three did not utilize real-time communications or processing, required small craft support in order to operate, and PMA was needed to detect mines in the area of concern.

This capstone project has identified and evaluated capability gaps in the MCM DTE sequence performed in the VSW zone in areas of denied access in support of amphibious operations. Realistic material solutions to bridge the gap in the 10-15 year timeframe have been developed and the best alternative has been recommended that reduces the DTE time, removes the man from the minefield, reduces burden of MCM operations on humans, and removes PMA. The comprehensive methodology utilized by this research can be used by the Navy for further development of future MCM systems. Although a final architecture recommendation has been made, further investigation is needed in key areas before the concept can be realized. These areas include the technical development of autonomous capabilities, research and investment in developing real-time OTH communication capabilities, data fusion from multiple sensors for mine detection and identification, and research into the best energy source for the recommended alternatives.

At the start of this project, six questions were articulated to guide the research to support finding a solution to the capstone problem. The following summarizes the answers that were presented within the body of this report.

1. Is it possible to completely remove the man/mammal from the minefield during UMCM operations?

As shown in Alternatives One and Two, removing the man and mammals from the minefield is possible. This can be accomplished using UUV technology in fully/semi-autonomous and tele-operated modes with a real-time communication network.

2. Is it possible to have a system or system of systems that can detect and clear a minefield path for amphibious landings within the required CONOPS time specifications?

A system of systems composed of Alternative One vehicles along with a separate neutralization vehicle would be able to detect and clear a minefield within timeframe requirements. Alternative One vehicle concepts can map a path through the minefield without having to physically disable any mines so that the amphibious landing force can make its way through and then at a later point effectively clears necessary targets in the minefield.

3. Will the MCM solutions present today or planned in the near future be able to handle current and future threats?

As shown through this report, the systems today can conduct limited MCM search, detect, identification and classification. Based only on the available open literature, it is unlikely that the current solutions and those planned for the near future will meet the need for conducting full DTE MCM operations.

The task of physical neutralization, not including avoidance techniques, in the VSW zone today is also a limited capability not only in technology but with doctrinal restraints. There are plans for developing UUV neutralization in the VSW zone that is projected to be available within the next few years. Based on available open literature it was determined that our system would be effective against future threats. This report has recommended an architecture that will be able to handle both current and future threats with the imposed requirement of stealth to support amphibious operations.

4. What is the greatest obstacle in reducing the DTE sequence timing?

At this point in time the greatest obstacle to reducing the detect-to-engage sequence timing is the lack of real-time analysis of the minefield. As shown by the results of the

research in this project, this can potentially be overcome by investing in establishing a real-time network capability through a buoy network or similar communications and data processing systems.

5. What alternatives exist to overcome obstacles to reducing the DTE sequence timing?

As noted in the response to question four, one method for reducing the DTE sequence is establishing a real-time communication network to enable in-the-loop mission analysis. This effectively could reduce the time required for target analysis portion of the mission by half.

Another method for reducing the DTE sequence time would be the use of autonomy during target processing. It has been noted by stakeholders and professionals in the MCM community that humans conducting mission analysis puts a huge burden on the operators and can be time intensive, inconsistent (dependent on the training the operator received), and at times produces an abundant amount of false targets. The introduction of data fusion, automated target recognition software could prove to reduce the time it takes to identify and classify a target.

Additionally it was found in this report that in order to search, detect, classify, identify, map and neutralize the minefield in the required 48 to 72 hours, multiple vehicles would be required.

6. For an implemented solution, what are the risks and benefits?

A risk identified using an autonomous based platform is that divers may not be allowed or available to visually identify and confirm a mine prior to having the mine being neutralized. This risk could be mitigated by ensuring maturity of the technology through proven capability and performance

A second risk of the recommended solution is false-negative or false positives reporting, in that the vehicle incorrectly identifies an object as a non-mine, when in fact it is a real mine or it identifies a non-mine as a mine. This risk could be mitigated by fine tuning sensors and detection algorithms based on environmental conditions and proofing out the performance to ensure target identification is accurate.

The main benefit from using an autonomous based platform is that it enables the removal of man and mammal from the minefield not only in the AO but out of the target processing loop.

B. RECOMMENDATIONS

The following recommendations are made:

1. Invest in development and employment of autonomy to remove operator burden.
2. Identify and invest in methods and structures to provide real-time communication specific to MCM operations.
3. Continue to research methods and solutions for OTH capabilities.
4. Invest in efforts to increase power availability and power management architectures.
5. Continue research methods for DTE reduction and identifying methods of efficiency for current system solutions.
6. Identify a Lead Systems Architect to manage MCM system interoperability.
7. Update MCM operational doctrine to reflect the current state of technology.

C. SUMMARY

The VSW environment has been identified as a difficult, diverse environment. There are unique challenges that a system design must meet to be capable of conducting the MCM mission with reliable results. The solutions of the future must be designed and managed to meet the needs of the stakeholders as well as be able to reliably perform as an affordable solution.

As technology of the enemy progresses, MCM technology design must change to meet this challenge. With a lead system architect identified it will ensure that an effective solution is achieved to enable interoperability among systems, rather than having several program offices and branches working individually on the same effort. The lead systems architect should have the oversight of the development of SoS for MCM operations and can liaison with Marine Corps representatives to ensure the developed MCM capability sufficiently addresses their needs.

Although stakeholders have indicated the need for DTE reduction and systems that enable single pass DTE operations, it has been assessed that neutralization should be completed separately. Minefield neutralization is complex and in order to support in-stride neutralization in the future, the neutralization platform will need to be a separate system in order to continue and complete the search, identification and classification of the entire AO.

As technology in search, identification, and classification progresses, it is necessary to continually reassess technology readiness in order to enable a change in MCM doctrine to allow for auto target recognition and neutralization. Current doctrine restricts certain aspects of autonomy and auto target recognition capabilities because of the requirement for targets to be identified and confirmed by divers before they can be authorized to be neutralized. Auto target recognition and autonomy algorithms are becoming more prevalent today and are on the verge of becoming a mature technology. The MCM community must be willing to accept this technology as an available capability if removing the living element from the minefield is to become a reality.

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APPENDIX A: CURRENT AND FUTURE MCM SYSTEMS

A. CURRENT SYSTEMS

1. Unmanned Underwater Vehicles

a. MK 18 MOD 1

Figure 76 displays the MK18 Mod 1 Swordfish, a small, two-person portable, low-cost UUV support craft tasked to locate bottom and tethered mine-like objects in specific lanes through the VSW zone. This UUV system utilizes integrated sensors and navigation technology and is launched to map the potential mines in the VSW zone for avoidance, or later clearance by other MCM assets. The MK18 Mod 1 Swordfish provides rapid object localization for confined areas (inlets, berthing areas, between piers and pilings, confined channels and rivers) and open areas (large open channels, harbors and anchorage areas) in up to 300 Feet of Sea Water (FSW). This UUV system is identical in configuration to the VSW Mine Countermeasures (MCM) MK 18 Mod 1 Swordfish Unmanned Underwater Vehicle (UUV) system and has an endurance of 10 hours at 4knots. The project office for the MK18 Mod 1 Swordfish/ Bottom Unmanned Underwater Vehicle Localization System (BULS) is PMS 408 (EOD).

Figure 76. MK 18 MOD 1 Swordfish UUV System

The MK18 Mod1 Swordfish shown has the advantage that it is of low cost and can be used on missions to locate mine-like objects in the VSW zones. This system requires a two person team to launch and recover the unit (AUVAC, 2007).

The MK 18 Mod 1 Swordfish is capable of navigating via acoustic transponders in long-baseline or ultra-short-baseline mode or via P-coded GPS. Upward and downward looking acoustic digital velocity log improves dead-reckoning accuracy. Onboard sensors include water turbidity, water temperature and conductivity, side-scan sonar, and downward-looking camera

(AUVAC, 2007). A disadvantage of dead reckoning is that any errors and uncertainties of the process are cumulative (since new values are calculated exclusively from previous values); therefore, any error or uncertainty in the value increases with elapsed time.

The MK18 Mod 1 has a thruster propulsion system that can sustain a nominal speed of approximately 1.5 m/s for 22 hours. It is limited to a maximum forward speed of 2.6 m/s for approximately 8 hours. The system is capable of a maximum depth of 100 meters and can be delivered by hand or a vessel of opportunity (AUVAC, 2007).

b. AN/AQS-20 Mine Hunting Sonar System

The AN/AQS-20 Mine Hunting Sonar System, shown in Figure 77, is a towed sonar mine-hunting system that can detect and classify drifting, moored, and bottom mines in deep and shallow water (AN/AQS-20A Minehunting Sonar System, 2008). It includes ahead-looking search, volume search, gap-filler, side-looking classification sonar, and an electro-optic identification device (Naval Mine Warfare, 2001). The AN/AQS-20 automatically localizes mine-like objects and provides the operator with a visual image and a contact data list. All mission data is recorded for post-mission analysis (AN/AQS-20A Minehunting Sonar System, 2008). Since the AN/AQS-20's sonar suite was designed for depths greater than 40 feet, it is considered ineffective in the VSW (Keller, 1 AUG 2007).

Figure 77. AN/AQS-20A Minehunting Sonar System

The AN/AQS-20A Minehunting Sonar System has the capability to detect and classify moored and bottom mines. The system however cannot neutralize threats (AN/AQS-20A Minehunting Sonar System, 2008).

c. Variable Depth AN/SQQ-32 Minehunting Sonar System

The AN/SQQ-32Minehunting Sonar System, seen in Figure 78, can be considered a surface MCM system since it is used as part of the onboard systems in the MCM-1 Avenger class. The system helps ship to detect and classify modern moored and bottom unburied mines at both deep and shallow waters over a wide range of bottom conditions and distances (AN/SQQ-32 Minehunting Sonar System, 2005). However, the AN/SQQ-32 system is not effective in the VSW zone as it is not optimized for harsh littoral environments against stealthy bottom mines. Typically, after a mine is detected by the AN/SQQ-32 system, it relies on a tethered AN/SLQ-48 Mine Neutralization System (MNS) to neutralize detected mines.

Figure 78. AN/SQQ-32 Minehunting Sonar System

The AN/SQQ-32 has the ability to detect and classify moored and unburied bottom mines. The system carries the advantage in that it detect mines in a wide range of conditions (AN/SQQ-32 Minehunting Sonar System, 2005).

2. Diver Systems

Current diver systems include the use of the MK 15 Mod 1 Underwater Imaging System (UIS), the AN/PQS-2A handheld sonar, and the MK 16 Mod 1 Underwater Breathing Apparatus. Although the diver systems present advantages in that they are easily launched, recovered, and can be used in a covert manner, they have the distinct disadvantage in that they put a diver, or team of divers in the minefield and have limited endurance.

a. Underwater Imaging System (UIS) MK 15 MOD 1

The Underwater Imaging System (UIS) is coupled with the Diver Visual Information System (DVIS) and provides divers with the unique capability of a handheld sonar system that provides navigational capabilities for MCM operations. The system comes equipped with the capability to record the detection and classification images of mine-like objects (Stuart, 2005). The system is capable of presenting, storing, and transferring digital target location, depth, and imaging data in a format similar to, or compatible with, current MCM Command, Control, Communications, Computers, and Intelligence (C4I) formats (Stuart, 2005). The system was launched in January 2005 and replaced the AN/PQS-2A hand-held sonar (Carson-Jelley, 2011).

In the area of VSW and bottom mines, the underwater imaging systems integration with a diver should allow for real-time classification and images of the objects based on the described capabilities. This allows for quick and easy deployment of mine countermeasure operations.

b. Underwater Breathing Apparatus (UBA)

The UBA is a special breathing suit designed to help divers perform MCM operations. It has a closed-circuit which recycles the air in the dive cylinders without producing bubbles to keep a clandestine profile. The UBA also has low acoustic signature and low magnetic signature that allows divers to safely approach acoustic and magnetic influence triggered ordnance underwater. The MK16 Mod 1 UBA version weighs 64 pounds and allows diver to operate underwater for up to 300 minutes (depending on initial pre-dive pressure, required reserve pressure, oxygen consumption by the diver, effect of cold water immersion on flask pressure). It can help divers to operate to a maximum depth of 300 feet of sea water (FSW) (US Navy Diving Manual Revision 6, 2008). Improvements in gas usage, dive duration, and depth capabilities provided by the UBA greatly increase the underwater duration to 4-6 hours (MK 16 Underwater Breathing Apparatus, 2007). PMS-EOD has already developed MK 16 Mod 2, an improvement of Mod 1, which includes Stealth EOD-M and VIPER-E (Stuart, 2005; Cobham Life Support, 2009) shown in Figure 79. Other UBA currently used by Navy divers are the MK 25 and its upgraded MK 25 Mod 2.

Figure 79. MK16 MOD2

The MK 16 Mod 2 has the direct advantage that it can complete the detect-to-engage clearance process, although it places the man in the minefield (Stuart, 2005).

c. Diver System Limitations

The use of divers in MCM operations has the advantage in that it allows for logical thought and hands-on processes through the mine hunting operation. The main concern with utilizing a diver system is the risk incurred by exposing the diver or team of divers to the dangers of the minefield. However, there are other limitations that affect the usefulness of a diver system.

The first of these limitations is the safety zone required for divers. Figure 80 shows the typical zone of safety that the diver must operate within to maintain a safe transit height above the ocean floor to avoid dangers from marine life and ground obstacles. This zone includes six feet below the surface of the water to make sure there is plenty of clearance from surface crafts. There is also a limitation of how close the diver can get to the ocean bottom; typically this value is two feet (Marine Corps System Command Infantry Weapon Systems, 2011). Due to the safety zone requirements, a diver requires a minimum operating depth of at least 10 FSW (Marine Corps System Command Infantry Weapon Systems, 2011).

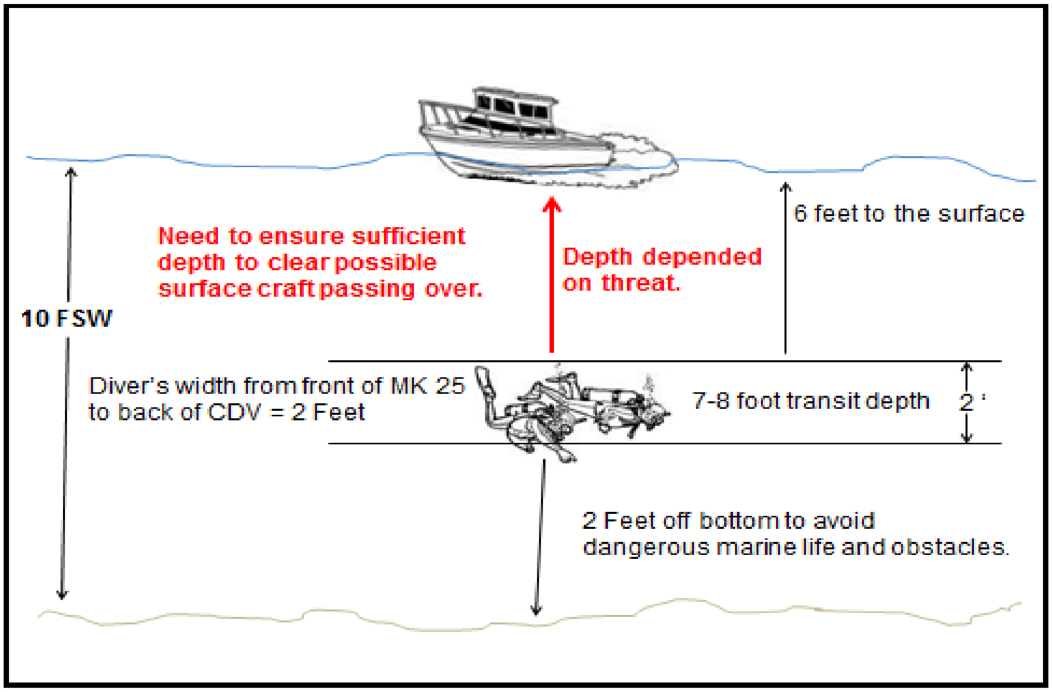

Figure 80. Diver Safety Zone Margins

Safety zone depiction for MCM divers. The diver's search depth is limited from the surface by proper clearance from surface ships above. The diver is also constrained to maintain an elevation of two feet from the sea bed to avoid marine life and obstacle hazards. (Marine Corps System Command Infantry Weapon Systems, 2011)

A second limitation of diver systems is the physical capabilities of the divers themselves. The speed, endurance, and air the diver can maintain factors greatly into the mission time. It can take upwards of 5 hours and 45 minutes for a diver to complete a sweep of a 250,000 yard^2 area under typical conditions (Marine Corps System Command Infantry Weapon Systems, 2011). Similarly, sea state may also play a role in deciding if a diving MCM mission can be carried out due to physical constraints and safety factors.

Further, despite its benefits in helping divers have better performance in MCM operations, closed-circuit oxygen diving presents a degree of risk to causing medical problems to divers such as central nervous system oxygen toxicity and convulsions, oxygen deficiency, carbon dioxide toxicity, middle ear oxygen absorption, and water leaking into the canister causing chemical injury (Stealth CDLSE, 2009). Systems such as the MK16 UBA, limits divers to operating in currents of less than 0.85 knots (US Navy Diving Manual Revision 6, 2008).

Because of these drawbacks, diver units are limited in performance compared to other systems and cannot satisfy large demands for rapid mine clearance to support amphibious landings.

3. Marine Mammal Systems

The US Navy currently has five Marine Mammal Systems (MMS) that are being used for MCM operations. These systems include the MK 4, MK 5, MK 6, MK 7, and MK 8. These systems involve training dolphins, sea lions, or a combination of both and integrating them with a team of humans to carry out sea mine hunting operations. MMS are advantageous because mammals have greater agility and endurance than most human divers, and also help in taking the man out of the minefield. However, mammals' lives are still being put at risk, as well as the human team that is working on the surface with the mammals. Due to increasing ethical issues, marine mammal systems have become more challenging to maintain proper training. These marine mammal systems also have the inherent risk of error due to the marine mammals' lack of understanding the situation that can sometimes lead to catastrophic ends.

a. MK 4 (Dolphins, Trainers)

The MK 4 system shown in Figure 81 utilizes dolphins for the detection, classification, and marking of sea and ocean mines (Marine Mammal Program: Fleet Systems, 2011). The MK 4 system is used for mines that are secured to the ocean floor by taking advantage of the dolphin's echolocation ability (Marine Mammal Program: Fleet Systems, 2011).

In the area of VSW and bottom mines, the MK 4 carries the advantage over sophisticated electronic acoustic devices in that it can be used in muddled seabed, marine growth, and other acoustically challenging areas where applications of technology may be deficient and harder to use (Marine Mammal Program: Fleet Systems, 2011).

Figure 81. MK 4 System

The MK 4 system utilizes dolphins to detect, classify, and mark possible threats in the VSW zone. This system can be used in the shallower areas of the VSW zone because of its effectiveness in marine growth areas and acoustically challenging areas (Marine Mammal Program: Fleet Systems, 2011).

b. MK 5 (Sea Lions, Trainers)

The MK 5 system in Figure 82 consists of a surface watercraft, a sea lion, and two handlers and is considered a "Quick Find" recovery system (Marine Mammal Program: Fleet Systems, 2011). The MK5 system operates by arriving at a threat recovery site and releasing a sea lion to the mine with a rope and mounting device. The sea lion attaches the mounting device to the mine and swims to the surface with the rope, where the object is pulled to the surface by the crew (Marine Mammal Program: Fleet Systems, 2011). The MK 5 system was developed by the Navy as a way to overcome the limitations of divers in the threat recovery area (Marine Mammal Program: Fleet Systems, 2011).

Figure 82. MK 5

MK 5 system is in the process of recovering a threat object. The possible sea mine is being mounted with a rope by a sea lion. The system has the advantage of low cost, speed, and agility (Marine Mammal Program: Fleet Systems, 2011).

This system is considered to be relatively inexpensive compared to dive teams and underwater remotely operated vehicles. The MK 5 system takes advantage of the sea lion's swimming speed and agility to expeditiously recover objects (Marine Mammal Program: Fleet Systems, 2011).

Specific to the area of VSW and bottom mines, the MK 5 system presents the capability of longer endurance times than humans and the capacity to operate in poor visibility and currents (Marine Mammal Program: Fleet Systems, 2011). The system has proven to have a very high recovery rate of over 95% (Marine Mammal Program: Fleet Systems, 2011). The exact system

capability and limitations in terms of endurance and speed are unknown for the purpose of this report.

c. MK 6 (Dolphins, Sea Lions, Trainers)

The MK 6 system is classified as a rapidly deployable force protection system that has been specifically trained with the unique ability to identify and find water-borne threats (divers/swimmers) that are near sea assets (Marine Mammal Program: Fleet Systems, 2011). The system consists of a system of dolphins, sea lions, and human trainers (Marine Mammal Program: Fleet Systems, 2011). The MK 6 has the ability to operate either as a roving patrol or as a sentry as shown in Figure 83. The system has most recently been used to support missions in operation Enduring Freedom (Marine Mammal Program: Fleet Systems, 2011). The system has the advantage that it can be easily and rapidly deployed in VSW zone. The exact system capability and limitations in terms of endurance and speed are unknown for this report.

Figure 83. MK 6

The MK 6 MCM system uses dolphins, sea lions, and human trainers to identify and find threats in the VSW zone. The system is easily deployed, but puts the mammal and human trainer at risk in forward deployed areas (Marine Mammal Program: Fleet Systems, 2011).

d. MK 7 (Atlantic Bottle Nose Dolphins)

The MK 7 system utilizes Atlantic Bottle Nose Dolphins that are trained to detect and mark locations of mines that are sitting on an ocean floor and buried under sea sediment (Marine Mammal Program: Fleet Systems, 2011). This system is primary used to clear channels for the safe shipment of personnel and materials through a given area (Marine Mammal Program: Fleet Systems, 2011). The MK 7 system was used during the 2003 Iraq war operation where the system played an integral role in the clearance of mines from Umm Qasr’s harbor to support allied force movement (Marine Mammal Program: Fleet Systems, 2011). The exact system

capability and limitations in terms of accuracy, endurance, and speed are unknown for the purpose of this report. Figure 84 depicts an Atlantic Bottlenose Dolphin in the MK7 configuration.

Figure 84. MK 7

The MK 7 system utilizes dolphins for the detection and locating of bottom mines. The system is considered easy to deploy because it does not require large ships or helicopters (Marine Mammal Program: Fleet Systems, 2011).

e. MK 8 Marine Mammals System (Dolphins)

The MK 8 MMS seen in Figure 85 is primarily used for the initial landing of forces. The system allows the forces to very quickly recognize and identify areas and channels that are safe for the landing of troops and machines (Marine Mammal Program: Fleet Systems, 2011).

Figure 85. MK 8 System

The MK 8 system is primarily used for MCM operations in the initial landing of amphibious forces. The quick identification of threats is advantageous to allowing the rapid and safe landing of troops/machines (Marine Mammal Program: Fleet Systems, 2011).

The MK 8 has the advantage that it can be operated with a very low profile (MK 8, US Navy). This is especially advantageous in the area of amphibious operations in the VSW areas, where it can be used for a surprise attack more easily. For the purposes of this report, the exact capabilities of the system in terms of accuracy, speed, and endurance were either not found or classified.

f. Marine Mammal Systems Limitations

MMS limitations are a mixture of ethical issues, endurance limitations, and minesweeping speed. It is hard to imagine a way that endurance and speed can be increased aside from better training of the mammals. However, increased training or sensor suites would come at an increased cost for small performance increases that would still be physically limited and would still keep the mammal operating in the minefield.

A. FUTURE SYSTEMS

4. AN/WLD-1 Remote Minehunting System (RMS)

The AN/WLD-1 Remote Minehunting System (RMS) in Figure 86 consists of semi-submersible UUV called the Remote Multi-Mission Vehicle (RMMV) that tows an advanced variable-depth AQS-20A sensor (Fifi, 2007). Its mission is to survey shallow coastal zones and to improve the picture of the current tactical situation with its detection, localization, identification and classification capabilities (Fifi, 2007). This system has 24-hour endurance and is capable of over-the-horizon, high-coverage search rates in deep and shallow water with a high probability of identifying mines (Lockheed Martin, 2010). The project offices for the AN/WLD-1 RMS are PMS 420 and PMS 403.

Figure 86. AN/WLD-1 Remote Minehunting System (RMS)

Developed by Lockheed Martin, the AN/WLD-1 is a UUV that utilizes an AQS-20A sensor (Lockheed Martin, 2010). It is designed with the capability to carry out detection, localization, identification, and classification in shallow waters (Fifi, 2007).

In the VSW zone, the AN/WLD-1 RMS system provides identification capability using an electro-optic sensor (Carson-Jelley, 2011). The system has the advantage that it performs real-time data synchronization with off-board systems, in addition having data storage capabilities (Fifi, 2007). However, the major disadvantage of the system is its size. At 23 feet and 7 tons (Fifi, 2007), the system is not easily launched or transportable.

5. AN/ALQ-220 Organic Airborne & Surface Influence Sweep (OASIS)

The AN/ALQ-220 OASIS, depicted in Figure 87, is towed from MH-605 helicopters or surface craft to provide organic, high speed magnetic and acoustic minesweeping capability (ITT Corporation Electronics Systems, 2008). OASIS is capable of satisfying the need for a rapid-coverage mine clearance capability required to sweep influence mines. The specific technologies used on the system are induced cavitations acoustics and programmable depth and altitude control that allow the system to operate at controllable depths (Almquist, Status & Issues for Assault Breaching System Technologies, 2005). The project office for the AN-ALQ-220 OASIS is PMS 495.

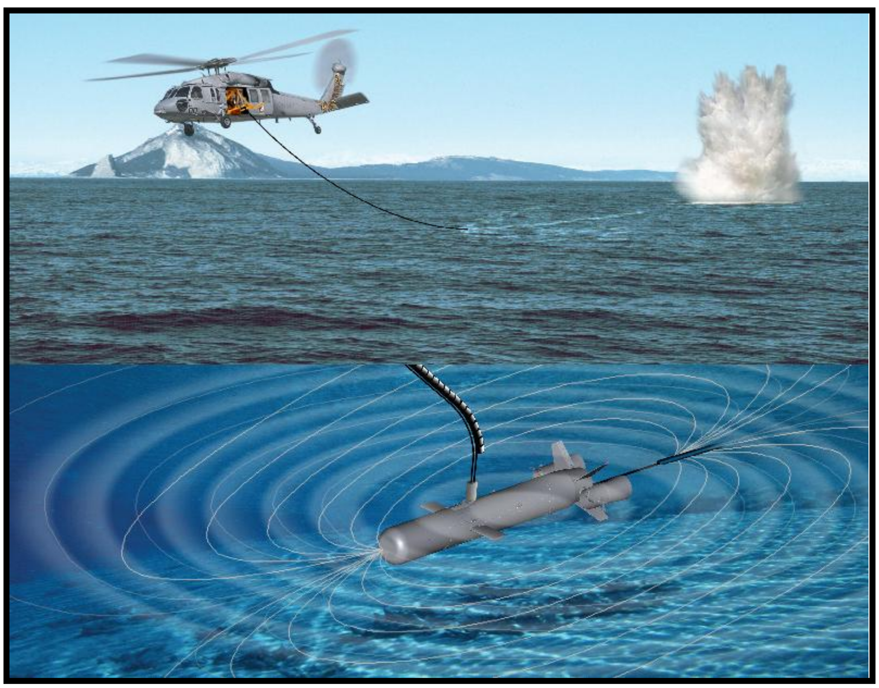

Figure 87. OASIS (Organic Airborne & Surface Influence Sweep-AN/ALQ-220)

OASIS (being towed by a helicopter) has the ability detect, localize, and identify mines in MCM operations (ITT Corporation Electronics Systems, 2008). The system can be used in both day and nighttime operations; however it lacks the complete capability to neutralize mines (North Atlantic Council, 2002).

OASIS carries the advantage that it can be used in straits and amphibious objective areas where mine hunting is not practical due to ocean bottom mud and high clutter (ITT Corporation

Electronics Systems, 2008). Due to weighing 930 pounds and being around 16-inches in diameter, the system is easily transportable and deployable, and recoverable (ITT Corporation Electronics Systems, 2008).

There are several weaknesses associated with the AN/ALQ-220 OASIS. Being a towed system, operations utilizing OASIS are not very covert. The MH-60 towing of the device would most likely give away the location on the beach that an amphibious operation would occur on. Secondly, due to the towed nature of the device, the use of the system is limited by the device towing the system (MH-60). In this case, there would most likely be weather and other environmental conditions that would limit the usefulness of the OASIS.

6. Organic Airborne Mine Countermeasure Module (OAMCM)

The OAMCM is an organic airborne platform that can perform end-to-end MCM capability using a helicopter as the Host Platform. OAMCM is a system-of-systems composed of modular components including the Towed Mine-hunting Sonar System (AN/AQS-20), the Airborne Mine Neutralization System (AN/ASQ-235), the Airborne Laser Mine Detection System (ALMDS), the Rapid Airborne Mine Clearance System (RAMICS), and the Organic Airborne and Surface Influence Sweep (OASIS)(Office of the Chief of Naval Operations Expeditionary Warfare Divsion (N85) & Mine Warfare Branch, 2012; Naval Mine Warfare, 2001). The capabilities of the Towed Mine-hunting Sonar System (AN/AQS-20) and the AN/ALQ-220 Organic Airborne and Surface Influence Sweep (OASIS) were described earlier. The additional capabilities of the OAMCM SoS are described briefly as follows:

The ALMDS shown in Figure 88 can detect, localize, and classify drifting and moored mines near the sea surface. ALMDS uses a high-powered blue-green laser technology Streak Tube Imaging Laser (STIL) Laser Imaging Detecting and Ranging (LIDAR), state of the art complementary metal oxide semiconductor cameras, and image processing to fill the gap of the AN/AQS-20 by being able to hunt mines into the VSW zone. However, the ALMDS and RAMICS cannot hunt bottom mines, and the RAMICS program was cancelled in 2011; limiting the applicability to this report.

Figure 88. ALMDS On Helicopter

ALMDS in use on a helicopter platform (Northrop Grumman, 2006). The system can detect, localize, and classify drifting and moored mines near the sea surface. The system takes advantage of high powered laser technology to complete this sequence (Naval Mine Warfare, 2001).

The AN/ASQ-235 Airborne Mine Neutralization System (AMNS) shown in Figure 89 is designed to reacquire and neutralize (with a shaped charge warhead placed very near a previously identified mine to cause high-order detonation) both unburied bottom and moored mines in shallow and deep water. It consists of a control console and a launching mechanism for four Archerfish unmanned underwater vehicles (UUVs) that are lowered from the helicopter. These UUVs are tethered with a fiber-optic cable and equipped with video and sonar sensors to detect and find anti-shipping mines. AN/ASQ-235's UUVs also carry an explosive charge to allow the operator in the helicopter to remotely dispose the anti-shipping mine (Naval Mine Warfare, 2001; BAE Systems, 2010; Raytheon Integrated Defense Systems, 2008). The AN/ASQ-235 has not yet been demonstrated for its capability to neutralize bottom mines in VSW at the time of this report.

Figure 89. AN/ASQ-235 Airborne Mine Neutralization System (AMNS)

The AN/ASQ-235 AMNS consists of a control console and launching mechanism (Raytheon Integrated Defense Systems, 2008). The system's overall design allows it to reacquire and neutralize bottom and moored mines (Naval Mine Warfare, 2001).

The combination of these components gives the OAMCM the capability to detect, localize, and identify drifting, moored, and bottom mines during day and night operations. The system however lacks the capability to neutralize bottom mines in the VSW zone. Even if the technology maturity can provide these modules their performance as desired, the OAMCM has significant vulnerabilities to attack in operations supporting amphibious landings due to its airborne operation. Additionally, its towing system has to be constrained to a fixed altitude that makes the helicopter vulnerable to surface-to-air weapons. Another discrepancy of this system is that its current technology is not designed to deal with modern types of influence mines that can detect sweeping signatures (North Atlantic Council, 2002).

7. Joint Assault Breacher System (JABS)

The Assault Breacher Systems (ABS) are naval mine neutralization systems and normally utilize explosive munitions as a means for mine countermeasures. Historically, explosive munitions have been used to excavate mine fields, destroy and damage, or deactivate mines either on land or underwater. Recently, with the advance in technology, a precision guided bomb can be used to dispense thousands of small neutralizers (darts) that can clear a mine field or clear lanes through which the landing forces can move safely and rapidly. The systems that utilize this method are referred to as Countermine Systems (CMS). The advantages of these methods are that their mine neutralization operations are faster than those of other MCM methods; they require less prior preparation for the littoral zones, and are not limited to the types of mines and the mine field environments.

One of the disadvantages of ABS is it requires proofing afterwards to eliminate remaining mines unaffected by the operation (Maropoti, James A. Col USMC (Ret), 2011). The other disadvantage is the ABS depends on other systems for mine detection and localization. The final performance of the ABS will depend on the effectiveness of sub-component technologies. These sub-component technologies have yet to reach maturity and may not perform as well as desired. Furthermore, the ABS does not address modern types of mines that have improved insensitivity to sympathetic detonation (North Atlantic Council, 2002).

One system that has already been demonstrated is the Joint Assault Breaching System (JABS). Other similar ABS systems to be developed are the HYDRA-7, Mine Obstacle Defeat System (MODS), and the Naval Gun Fired System (NGFS).

The Joint Assault Breaching System (JABS) utilizes existing Navy and Air Force Systems for the deployment and employment of a dispense mechanism to deliver Countermine Counter-Obstacle (CMCO) warheads. The JABS can adapt the Joint Direct Attack Munition (JDAM) guidance kit to convert existing warheads (MK-83/BLU-110, MK-84, BLU-109 and MK-82) to accurate guided "smart" bombs. These bombs can be delivered by strategic bombers B-52, B-2 or supersonic planes such as the F/A-18 or B-1B. The JABS has been demonstrated in neutralizing mines in Beach Zone (BZ) and Shallow Zone (SZ) zones. Further tests have been done to demonstrate its capability against bottom mines and obstacles in the VSW zone. The Navy is considering a plan to deliver an expanded capability for neutralization in the VSW by FY 13 (Cobham Life Support, 2009). The Coastal Battlefield Reconnaissance and Analysis (COBRA) with Fire Scout Vertical Takeoff Unmanned Air Vehicle (VTUAV) can be used in conjunction with the JABS to detect the existence of mines in these zones (Almquist, Standoff Systems & Technologies for Near Shore Mine Countermeasures (MC), 2002). JABS is depicted in Figure 90.

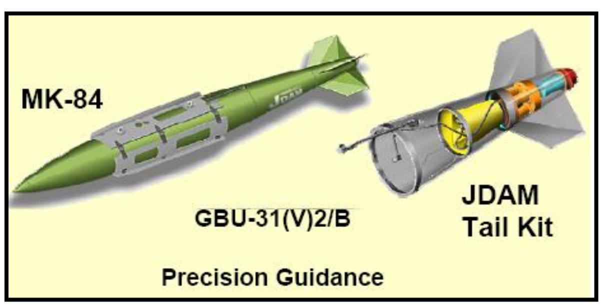

Figure 90. JDAM Assault Breaching System (JABS)

The JDAM assault breaching system is a precision guided neutralization system in MCM operations (Almquist, Status & Issues for Assault Breaching System Technologies, 2007). These munitions can be delivered by strategic bombers (B-52, or B-2) or supersonic planes (F/A-18 or B-1B) (Almquist, Standoff Systems & Technologies for Near Shore Mine Countermeasures (MC), 2002).

Similar to the JABS, the MODS (Figure 91) utilizes the JDAM guidance kit to deliver warheads equipped with either chemical darts for mine clearance or continuous rod warhead to obstacle clearance. The JDAM kit also provides Global Positioning System and Inertial Navigation System capabilities for accurate guidance. The MODS can be launched from F/A-18 aircraft and guided to the target area where it performs a terminal maneuver that results in it being oriented in a vertical position. The chemical darts or the continuous rod warheads are then dispensed from the MODS (Almquist, Standoff Systems & Technologies for Near Shore Mine Countermeasures (MC), 2002).

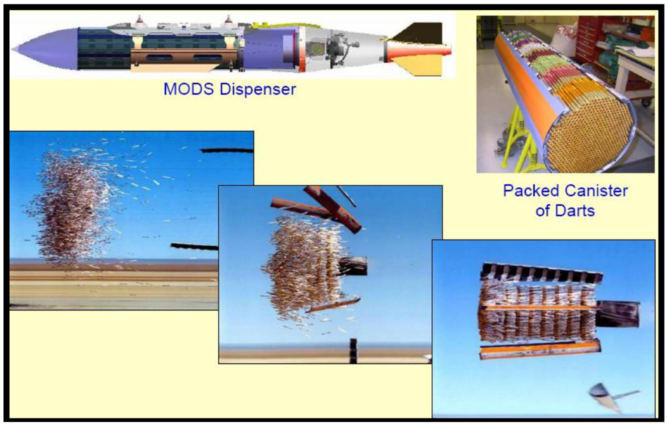

Figure 91. Mine Obstacle Defeat System (MODS)

The Mine Obstacle Defeat System (MODS) is used in mine neutralization operations (Almquist, Status & Issues for Assault Breaching System Technologies, 2007). The system uses global positioning systems for accurate guidance to possible threats (Almquist, Standoff Systems & Technologies for Near Shore Mine Countermeasures (MC), 2002).

The HYDRA-7 (Figure 92) is an advanced mine-counter warhead that utilizes a Tactical Munition Dispenser (TMD) to deliver thousands of sub-munitions. These sub-munitions are reactive material filled darts that can cause the high explosive within the mines to burn or detonate. Each of the sub-munitions has a guidance system and propulsion system to accurately guide it to the targeted area. The reactive material generates intense heat and pressure when subjected to a mechanical or thermal stimulus. The sub-munitions initiate a terminal maneuver upon reaching the targeted area that result in each being oriented nearly vertical with respect to the ground target. The propulsion system then increases the velocity and the darts are dispensed from the sub-munitions. The increase in velocity is required in order for the darts to be dispensed with sufficient kinetic energy to destroy the mines. The HYDRA-7 is currently deployed on an F/A-18 aircraft (Almquist, Standoff Systems & Technologies for Near Shore Mine Countermeasures (MC), 2002).

Figure 92. HYDRA-7 Darts

The HYDRA-7 dart works by employing a Tactical Munitions Dispenser (TMD) to distribute sub-munitions darts that cause a threat to detonate or burn (Almquist, Status & Issues for Assault Breaching System Technologies, 2007).

The Naval Gun Fire System (NGFS) system utilizes the same warheads as the MODS; however the warhead can be delivered from a precision guided 155-mm naval artillery shell. The shell is a scalable version of the Best Buy Projectile used for Advanced Gun System (AGS). When the projectile approaches the targeted area, it performs a terminal maneuver that gives the projectile a vertical orientation. At this point the payload is dispensed from the projectile (Almquist, Standoff Systems & Technologies for Near Shore Mine Countermeasures (MC), 2002).

8. MK 18 Mod 2

The MK 18 Mod 2 Kingfish, seen in Figure 93, is a program that has been initiated as an upgrade to the MK 18 Mod 1 UUV. The primary platform is a modified REMUS- 600 that is intended to enable larger ACR for detection of moored and bottom mines at the reduced risk to the operators and MMS. Initial testing has shown that improved sensor capabilities for conducting MCM low visibility searches in high clutter and high burial conditions within the VSW zone. The MK 18 Mod 2 has a depth rating of 600m and current testing has proven endurance greater than 20 hours at normal operating speeds. The MK 18 Mod 2 is considered a light-weight system and is approximately 600lbs. Due to the size comparison to the MK 18 Mod 1, the Mod 2 cannot be lifted by operators. Initial concepts for the system deployment include the use of an 11m RHIB with a custom launch and recovery system (Simmons, 2011).

Figure 93. MK 18 Mod 2 System

MK 18 Mod 2 System being deployed from small craft in a littoral region (Simmons, 2011).

B. NATO SYSTEMS

1. MUSCLE AUV

NATO AUVs aim to take advantage of the safety factor involved with these systems. The NATO system Muscle is one such of these systems. The system carries the capability to effectively hunt and classify mines by taking advantage of Synthetic Aperture Sonar, (SAS), (NURC 2009 Research Technology Highlights, 2010). This new technology is a method of compiling data from multiple sonar pings and processing the data into an actual image (NURC 2009 Research Technology Highlights, 2010). The technology has been under development since 1996, and is now considered a mature technology. The advantage of this system is that it allows for larger areas of sea bottom to be scanned in a faster and more effective manner than current methods (NURC 2009 Research Technology Highlights, 2010).

The MUSCLE AUV (proven through a set of sea trials) has shown the capability to hunt mines, with high accuracy and speed compared to previous systems, in the challenging conditions experienced in very shallow waters containing sands, ocean bottom clutter, and rocky bottoms (NURC 2009 Research Technology Highlights, 2010).

The MUSCLE system comes with several advantages in the VSW zone against bottom and buried mines. Its aptitude for performance in ground clutter and rocky bottoms allow the unit to be able to look for and discriminate bottom mines. The system’s use of Synthetic Aperture Sonar (SAS) allows it to better recognize bottom and buried mines than previously fielded systems. Due to the system being somewhat autonomous, it can be used somewhat covertly.

There are, however, a few disadvantages associated with the MUSCLE system. As can be seen in Figure 94, the system must be launched by a ship and crane/lever system. This can be a limiting factor with the system, as a crew and ship would most likely lead to a large logistical and support footprint involved with the system.

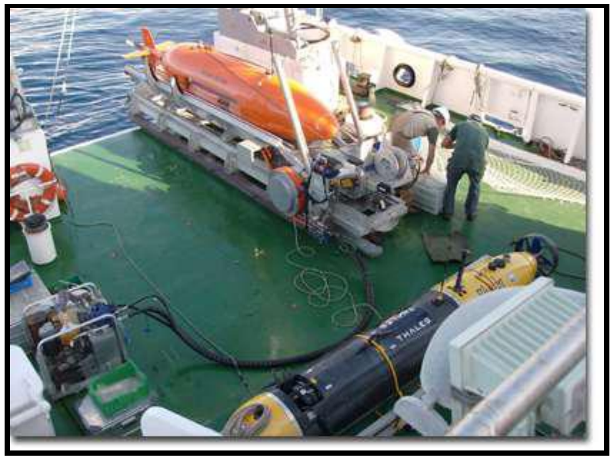

Figure 94. HUGIN (Top) & Muscle (Bottom)

The HUGIN and MUSCLE AUVs are NATO systems that can be used to provide high-resolution, high-speed mapping and imaging of the sea bed (Hagen, 2010). Although quite large, the system can be effective against bottom and buried mines in MCM operations (NURC 2009 Research Technology Highlights, 2010).

2. HUGIN AUV

The HUGIN is another NATO AUV system that offers a suite of underwater remote sensing capabilities. The system operates without cables, tethers, or wires (HUGIN AUV, 2011). The HUGIN offers the capability of high-resolution, high-speed seabed mapping, imaging, ocean-bottom searches, monitoring, and undersea inspections (HUGIN AUV, 2011). These abilities are currently being applied in the area of sea mine countermeasures. The HUGIN systems are self-handling. This offers the capability to allow the systems to navigate, and steer themselves to achieve mission objectives independent of constant human interaction (HUGIN AUV, 2011). Due to the HUGIN's capability to operate without cables and tethers, the system has the advantage in that it can be operated covertly. This lends to the ability to use the system on a landing area in VSW without the enemy knowing. The systems high speed/resolution mapping of the sea bed has the ability to be very advantageous against bottom and buried mines.

As in the case of the MUSCLE, the HUGIN, also pictured in Figure 94, is quite large as well, and must be launched using a ship (NURC 2009 Research Technology Highlights, 2010). This could potentially hinder the ability to launch and transport the system to areas where an amphibious assault may be planned.

IX. APPENDIX B: STAKEHOLDER LIST AND INTERVIEWS

Table 36 lists the questions that were developed from the initial stakeholder research and stakeholder input as a result of the Threat and Capabilities analyses. Stakeholder questions were directed at the relevant stakeholder as indicated in the table along with the resultant response. A non-response by a stakeholder is shown in the table by a question being directed to a stakeholder and no response indicated in the response column for that stakeholder.

Table 36. Stakeholder Questions and Responses

Table captures the question and answers session conducted with each of the major stakeholders. Information provided was used in the threat and current capabilities analyses and influenced the direction for the Capstone project.

	Question	**Directed at What Stakeholders**	**Answer**
1	Is there a system out right now that can detect and clear a path in a minefield that keeps the man/mammal out of the minefield?	PMS-408 Panama City ONR PMS-403	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011** "No, there is not a complete solution to remove the man from the minefield. Neutralization is still not automated and missions still require support divers to be close to the mine field. The only technology that maybe close to answering this would be JABS. **Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011** No not right now. MMS are the primary means of MCM operations. The MMS have allowed the DIVER to stay out of the water, but the man must stay close to the minefield to support the mammal. MMS are really great at low false positives. There is not a technology out there that can compare to MMS accuracy of low false positives. MMS also are great at buried mines (technology is only scratching

	Question	Directed at What Stakeholders	Answer
			the surface), and detection in a cluttered environment. In comparison of MMS and UUVs in flat sandy bottom environments, UUV performance is approaching comparable levels to MMS. MMS also have an advantage over UUV's in that has a shorter DTE time. Dolphins can detect and mark or detect, mark and neutralize in one pass. (Mission dependent) **Aamir Qaiyumi NSWC-PCD Interview 19 Aug** The underwater systems that exist today and in future development only eliminate the man to a point. They are still required to be within a certain distance from the minefield to retrieve the UUV. The current MK18 Mod1/2 is limited also by endurance. OTH launch and recovery platforms are also in very preliminary stages. There is also no "one" system that can complete a full DTE sequence. Right now the MK18 Mod1/2 complete SCM-IR (search, classify, map, identify, reacquire) and there is limited development for the neutralization phase. There is only one neutralization notional concept of SCM-IR at this point and the mission includes using 3 different vehicles, one to do SCM and another to do IR. A third neutralizer vehicle would come in to do the last step. The only neutralization UUVs that is being worked on now for PMS 408 is the EUNS (Extended Underwater Neutralization system) and is in the primary development stage, not very mature. **LCDR John Schiller, EODMU1 XO Interview 9-2-2011**- No, this capability is still not proven and not with current technology. There is hope with future concepts that we can meet removing the man/mammal from the minefield. UUVs are great at locating objects but produce too many false positives. MMS are great for

	Question	Directed at What Stakeholders	Answer
			detecting buried objects and nothing on the technology side has been able to reproduce their capability. Also, significant work needs to be done in technology with neutralization.
2	With systems that exist today, a. How long does it take to complete an MCM mission? b. How does that match up to current mission requirements? c. Will future requirements change in the DTE process change the CONOPS to match system capability or invest in SE type processes to help get closer to solve the problem?	PMS-408 Panama City ONR PMS-403 NMAWC	**Matt Clements – (ITT Technical Representative EODMU1) interview 8-29-2011** "There are many factors that are involved in how long a DTE should take. It really depends on several factors: • ACR-(Area coverage rate) • Size of the area • The need to be clandestine or not • Is the environment permissive or not • Water depth • Salinity • Environment (temp, currents, water clarity) • Percent clearance required The search should consist of 3 phases with UUVs: Intelligence Preparation of the Operational Environment (IPOE), Refined search and IR and then neutralization if time permits/mission allows" **Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011 -** With MMS, it depends. MMS cannot cover such large areas as UUVs. The dolphins will be worn out if required to cover large areas. MMS will still take almost 3 days or more and unlike UUVs, dolphins cannot do search area patterns. The MMS swim in sections called "swim lanes". Dolphins take markers to the detected target and mark it with either location markers (MK8) or marker/neutralization (MK7) components (mission dependent). MMS cannot do mosaicing like UUVs (combine strips of sonar

	Question	Directed at What Stakeholders	Answer
			images to make a map of the area), but mine feedback is closer to "real time" since MMS systems do not have any time consuming data download requirements. If MMS were used in combination with UUVs, there is a potential to reduce the DTE to 2 days. UUVs could potentially run the SCM mission and dolphins can run the second pass and neutralization phase. **Aamir Qaiyumi NSWC-PCD Interview 19 Aug -** With current systems, it would take a minimum of 3 days with personnel working 24hrs a day. This would also involve using all the human/technology assets employed and with no equipment failures. To get the technology to match the CONOPs, a notional mission execution may be like this: Day 1/Phase one: IPOE-Intelligence Preparation of the Operational Environment. Day 2/Phase two: SCM mission Day 3/Phase three: IR and neutralize if possible In regards to giving an answer to "2c."; Mr. Qaiyumi thought that in the future that both the CONOPS and the SE process would need to change. He expressed that at this present time there is a gap between the maturity of the technology and the expectations of meeting the requirements of the CONOPS.
3	What is the requirement for amount of time it should take to clear a path in a minefield to support amphibious landings?	PMS-408 Panama City ONR PMS-403 NMAWC	**USMC Capt Peter Moon -29 Aug E-Mail** "Clearance objective for MCM operation is 48 hours from the start of overt operations. 72 is the threshold." Overt operations can be characterized as anything that tips our hand permitting the enemy to reinforce and counterattack. Amphibious landings are dangerous enough

	Question	Directed at What Stakeholders	Answer
			without completely giving away the very valuable element of surprise. This is clarified as in a letter from CG MCCDC (Commanding General Marine Corps Combat Development Command) to CNO in 1999." **Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011:** MCM missions with MMS are not always executed as practiced in training. In training MMS execute the full DTE sequence for the entire area. MMS mission execution in practice: Dolphins will swim 8 lanes in an area where a projected amphibious landing area is expected and complete detection. Out of the 8 lanes, 4 lanes with the least amount of targets are cleared with mines being neutralized. **LCDR John Schiller EODMU1 XO Interview 9-2-2011-** Although the USMC may quote 48hrs threshold and 72hrs objective as a requirement for MCM to conduct clearance operations, our capability is not there yet. It's very dependent on size of the area, environmental, and bottom type. Also consider the effort in preparation for an area search. There are logistical support considerations for early set up, identifying a ship of opportunity and time for MMS to get adjusted to the area.
4	In some our reading, it has indicated that MCM systems require post mission analysis (PMA) of the data that is collected to locate and classify mine like objects (SEA Cohort 14, 2008).	NSWC-Panama City, NMAWC, PMS-495, PMS-408, PMS 420	**Bob Stitt. ITT Techrep MMS Trainer/EODMU1, Mod 1NSWC-PCD:** MMS doesn't need PMA.
	a. Is there system or systems that don't require (PMA) in order to locate and classify mine like objects?		**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:"MMS does not require PMA, to a point. They still have to search and mark positions and be verified by

	Question	Directed at What Stakeholders	Answer
			divers."
	b. If not, what is the minimum desired time to conduct PMA?		**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:" It should be a 1:1 ratio or mission run time compared to analysis time. 1 hour of UUV search time to 1 hour of a human looking at the data (or less)." **Aamir Qaiyumi NSWC-PCD** (Less than a 1:1 ratio). The community has a desire to stay at this rate or lower. From a technology development standpoint, it is recommended that PMA uses automated ways to interpret and assist the analysis process to recognize targets in sonar data. There is, however, an issue with this because technology like this is still being developed and PMA operators do not yet trust Auto Detection enough to really trust and rely on it.
	c. What is the maximum desired time to conduct PMA?		**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**: " No greater than 1:1" **Aamir Qaiyumi NSWC-PCD** (WLD-1 – 1:3 ratio - Human Related problem -- Keeping this as a problem)
	d. Where and who will conduct the PMA? Will it be done on one ship or all ships containing organic MCM systems required to perform the PMA?		**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**: "PMA is conducted after the initial IPOE/SCM mission and it is currently not in real time. PMA is mostly done at shore sites due to MK18 Mod2 are not approved for shipboard use or a fielded item. MK18 mod1 is also limited due to its limited use in the field." **Aamir Qaiyumi NSWC-PCD** "There is no Answer to this yet. There are several problems related with getting UUVs on Amphibious platforms. Mainly due to the big problem for fire

	Question	Directed at What Stakeholders	Answer
			suppression system with the MK18 Mod2's large - Lithium Battery. The MK18 Mod2 also weighs 600lb. Although the footprint is not officially defined, it is estimated to be fairly large. " **LCDR John Schiller EODMU1 XO Interview 9-2-2011**- PMA at this point is a real concern. PMA performance is more a matter of training the operator and the performance of the operator to find targets. I have no doubt the system will find and see the target, but will the operator?
	e. How is the data transmitted to ship responsible to perform a PMA?		**Aamir Qaiyumi NSWC-PCD** Currently, the EOD team launches UUV and retrieves it to down load the data. The data is transferred over to the PMA operators. The desire for future capability is to have Wi-Fi radio communications and upgraded acoustic communications to download data in real-time.
	f. Is there a desired way the data should be transmitted to the ship?		**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**: "Overall concerns with PMA: it takes a lot of training to prepare someone to assess sonar data. Due to high turnover rates, it's difficult to keep trained personnel in the unit. There is not a "UUV rating" or NEC. Analysis of the data is done by humans staring at sonar images on computer screens. Humans get easily fatigued and could miss targets or miss classify. The more search data collected, the longer a human has to stare at the screen. The more complex the ocean bottom is (cluttered), the more time it will take the human to go through the data. Implementation of Auto Target Recognition (ATR) would help the human sort through all the data, but it needs to be mature technology. We have to trust that it is working and are able to rely on it. It needs to be accurate and reduce false alarm targets and false positives."
5	What is the endurance required for MCM		**Matt Clements – (ITT Technical Representative EODMU1)**

	Question	Directed at What Stakeholders	Answer
	AUVs 1. Threshold ()? 2. Objective ()?		**Interview 8-29-2011**: See current MK 18 Mod1/2 which state (Mod1 Threshold 9 hours at 4 KTs – Mod 2 is 20 hours) (Simmons 2011)
6	From our reading the AN/WLD-1 has been deployed on USS Bainbridge and will be deployed on LCS(SEA Cohort 14, 2008): 1. What is the maximum time allowed to deploy an AUV from a ship? 2. What is the maximum time allowed to recover an AUV from a ship?		Stakeholders did not provide an answer to this question.
7	Is the Navy planning to develop a MCM AUV that can be deployed from a Helicopter or a Submarine (SEA Cohort 14, 2008)?		Stakeholders did not provide an answer to this question.
8	Doctrine says that MCM operation will emphasizes the clearance of mines in the transport area, fire support area, and sea approaches to the landing beaches(JP 3-02, 2009): 1. Is the priority for clearance given in this statement? (In other words will the transport area need to be cleared first before the approaches or will this be done simultaneously?) 2. If they are done in sequence; how much time is given to clear the control ship station, approach lane, AAV launch area, and boat lane?	PMS-340 NMAWC	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:"UUVs have been used for amphibious landings in the past, but in reality amphibious landings are not widely practiced today as often as they should be. Some operations in the past using UUVs with NSCT-1 (old name for EODMU-1): Port UMM QASR, 1st gulf war. Although in training we always go through a full DTE, in practice it is not done that way. We plan for what is necessary and leave secondary issues for later if we can get to them."

	Question	Directed at What Stakeholders	Answer
9	What threats are of the biggest concern in MCM currently?	NMAWC PMS-408 PMS-340	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**: Bottom/buried mines are the biggest threat right now. We need to keep and maintain low visibility. Efforts need to keep making progress for getting people out of the field and make our technology robust to handle a multi-threat environment" **Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011:** Buried mines, and complex area searches: MMS are the best detection asset for this currently. **LCDR John Schiller EODMU1 XO Interview 9-2-11**- Mine warfare targets in VSW are small contact mines, large magnetic signature, influence mines. The mine threats are changing to plastic and composite type materials. These materials are developed so that sea growth is encouraged to grow on the target, making it harder to detect.
10	Where do you consider the biggest capability gap to exist right now?	ALL	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:" –Needing to have a human post process the data causes errors, false positives, and extended length of processing. There is a great need for Automatic Target Recognition (ATR) capability. It needs to progress faster. -Communication. Communication meaning there is a lack or real time capability. The UUVs are sent out on a 4-5 (or more) hour mission and must be collected by support boats, driven back to shore to download data. Data down load is variable, but as discussed above, it can take 1 hour or more to review 1hr of sonar

	Question	Directed at What Stakeholders	Answer
			data." **Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011:** Technology is not advancing fast enough. Technology needs to continue to work on reducing false positives to the performance of MMS. **Aamir Qaiyumi NSWC-PCD Interview 19 Aug -** A big gap right now is the capability in identification. There is a big perception gap of trusting the sensor's ability. There is no silver bullet system in MCM, no one system can perform in every environment (temp, depth, current). Current and future development of Auto Target Recognition (ATR- autonomy behavior) will be a great thing if operators/users trust in the performance of the technology. ID is something that in the MCM world has be primarily "visual" detection/identification of the threat. Transition is not 100% for trusting ATR. **LCDR John Schiller EODMU1 XO Interview 9-2-11**- Sensor maturity. The UUV platform is stable, but the sensor payloads are not.
11	What is the footprint requirements for MCM mission module equipment aboard ship (i.e. How much room do you have on the platform to support the MCM equipment)? – Weight and size requirement	PMS-420 PMA-261 PMA-299	**Danny Sinisi, PMA-299 OAMCM SEIT Lead** - I do not have that info at my fingertips, but I do know it is significantly smaller than the HM DET footprint
12	Current Doctrine states that logistical support for an Airborne Mine Counter Measures (AMCM) deployment requires a 90 day pack up that weighs 72,000 lbs and	NMAWC PMS 420 N852	**Saroch, George B CIV PEO LCS, PMS 420 E-Mail to Paul Welsh 8-22-2011**: Just so you know, MCM-1 and MH-53E do little to no VSW work. That work is primarily accomplished by the EODMU units with mammals/divers deployed from Combat

	Question	Directed at What Stakeholders	Answer
	occupies 7000 square feet. Additionally it requires berthing and messing for 450 personnel (Marine Corps System Command Infantry Weapon Systems, 2011; MCWP3-13, 2011; MCWP3-13, 2005). Additionally the Navy got rid of its only MCM command ship, the USS Inchon. The Navy plans to start retiring MCM ships in 2008 with the mission being taken over by the LCS in 2017(Munoz, 2011). If the Navy is no longer is going to deploy Mine type ships; further equipment and men must be deployed on other amphibious ships or LCS. The LCS will have only 35 additional berthing accommodations (O'Rourke, 2011). This means to deploy 450 AMCM personal to support an Amphibious Operation; the operation will require 13 LCS to perform the AMCM mission alone. This does not include the MCM mission.	PMA 299 PMA 261 N880	Raiding Craft that are embarked from Amphibious ships. There is plan to incorporate VSW capability in the out years from the LCS primarily from VTUAV with COBRA/ALMDS and neutralization utilizing JABS. **Aamir Qaiyumi NSWC-PCD Interview 19 Aug -** Even if LCS takes a modular approach, it still limits the operational capability of the LCS platform. They would have to pull into ports to exchange the load out package, possibly exchange personnel. It's a huge logistics nightmare. One possibility would be to have UUV systems deployable OTH and controlled by shore based operators (like how AUVs are controlled from the US – like a video game!). The LCS would only have to carry the vehicle. No extra manning, limited training on launch and recovery.
	a. Does this mean AMCM operations may not be part of an Amphibious Operation – or is the contingent significantly reduced?		**Danny Sinisi, PMA-299 OAMCM SEIT Lead -** The contingent aboard LCS is significantly reduced.
	b. If the number personal supporting MCM operation must be reduced – what is max number of personal that will be allowed to support any or all of the MCM operations?		**Danny Sinisi, PMA-299 OAMCM SEIT Lead -** The LCS aviation DET will consist of approximately 23 people.
	c. With the current plans for future MCM assets what is the maximum		Stakeholders did not provide an answer to this question.

	Question	Directed at What Stakeholders	Answer
	number personal being planned to operate and maintain those systems?		
	d. Will this make size constraints on the packing and manning of the MCM assets?		**Danny Sinisi, PMA-299 OAMCM SEIT Lead** - Yes, LCS size being the driver.
	e. Is there size constraint requirements being place on future MCM assets?		**Danny Sinisi, PMA-299 OAMCM SEIT Lead** - Same as d
13	Is a destruction method approach versus a removal from area approach preferred?	NMAWC PMS-340	Stakeholders did not provide an answer to this question.
14	In the MCM DTE process, what phase is most critical? Is there a phase in your opinion that lacks current progress/research?	ALL	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:"Ensuring success of clearance of the mine field is critical. This starts at the planning level. An unknown area really makes a difference, especially when programming the UUV. It has to know specific details in order to do its mission. In the short term its identification and classification: ATR should help improve this. In the long term its real-time capability and getting improvements to neutralization" **Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011:** Detection and neutralization. Lacking technology that is comparable to false positive capability of MMS (classify phase) **Aamir Qaiyumi NSWC-PCD Interview 19 Aug -** Detection is the most critical. You need the system to detect stuff to be able to have the operators look at the sonar images. The MCM community lacks a system that is adaptable to all environments.
15	In today's MCM, what types of constraints exist that make the task of DTE difficult?	NMAWC PMS-340	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:" (a.) –Environmental, (b.) -some

	Question	Directed at What Stakeholders	Answer
	(Lack of current system performance? Operational constraints?)	PMS-408 Panama City ONR	technology constraints (systems not robust enough), (c.) -UAVs are so advanced in comparison to UUVs. The concept is the same, but the communication underwater and dealing with the environment makes the problem so much harder, (d) -current UUV neutralization techniques are not complete or mature yet. Because of doctrine requiring visual confirmation and that technology is not trusted or mature enough to provide a solution; it makes the task very difficult". **Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011:** MMS have such a large footprint. They take up a whole well deck on an amphibious ship. **Aamir Qaiyumi NSWC-PCD Interview 19 Aug -** Doctrine for identification phase. Current doctrine requires a visual (camera or video) to identify the mine type. Sonar images can practically be as clear as a picture, but cannot be used to ID. If sonar images were allowed to be used in ID, it would change a lot of things. Scientists are also causing slow progress in the ID phase. Most of them are concerned with detecting images, not necessarily classifying them. Scientists should be working in all the DTE phases. Environments also cause a constraint, current, salinity, temperature, turbidity. Within each program office of development systems, there is lack of consistency with human/system interfaces. (PMS 408 uses COIN to MEDAL, NMAWC is taking an EPMA approach and these systems don't talk to each other and can't share information.) **Danny Sinisi, PMA-299 OAMCM SEIT Lead** –Yes, the environment impacts performance.

	Question	Directed at What Stakeholders	Answer
16	What is the most likely operational environment we will encounter? (i.e. what are the temperature, sea state, pressure, salinity, currents, etc?)	ALL	**From Performance Specification: Paragraph 7.1** UUV shall be capable of being transported, deployed/launched, operated, and recovered in sea states (SS) up to SS 3. SS shall be measured at the 40-foot curve. SS 3 is defined as wind velocity of 11-16 knots (KTs) with small waves 0.5m to 1.25m high, becoming longer; numerous whitecaps.(PMS 408, 2007) **From Performance Specification: Paragraph 8.2.1** The UUV System shall be capable of operating in water temperatures from 32^{o} F (0^{o} C) to 90^{o} F (32^{o} C). Operational Water temperature is defined as the water temperature while the UUV and the auxiliary equipment intended for use in/underwater are deployed for the UUVs required endurance. **From Performance Specification: Paragraph 8.2.2** The UUV System shall be capable of operating in air temperature (protected from direct sunlight) from 0^{o} F (-18^{o} C) to 109^{o} F (43^{o} C). Operational Air Temperature is defined as the air temperature while the UUV system is deployed during the 4-hour search-classify-map portion of the mission. **From Performance Specification: Paragraph 8.3** The UUV System shall be operable after encountering thermal shock associated with exposure to temperature extremes of 0^{o}F (-18^{o} C) to 109^{o}F (43^{o}C) (air) and 90^{o} F (32^{o} C) to 32^{o} F (0^{o} C) (in-water). **From Performance Specification: Paragraph 7.2.1** The UUV shall be able to operate (i.e., transit and maneuver, not search-classify-map) at water depths of up to 300 FSW. **From Performance Specification: Paragraph 7.2.2** The UUV

	Question	Directed at What Stakeholders	Answer
			shall be able to operate (i.e., transit and maneuver, not search-classify-map) at the surface of the water. **From Performance Specification: Paragraph 7.3** The UUV System shall be able to operate in a current less than or equal to 2 KTs flowing in any direction. **From Performance Specification: Paragraph 7.4** The UUV and all other components intended for in-water operations shall be able to operate in water having a salinity level of 0 to 45 ppt. **From Performance Specification: Paragraph 7.5** The UUV shall have the capability to operate to the specifications of this document in turbidity conditions of up to and including 66 mg/l (~ 8 nephlometric turbidity units (NTU)) of suspended particulate matter as measured by a formazin calibrated optical backscatter meter.
17	Amphibious Operations using AAVs can be conducted in sea states 1 through 4. However, it is not recommended to be conducted in Sea state 4 and above (MCWP3-13, 2005). What sea-state should a MCM system operate (Threshold & Objective) in the VSW?		**From Performance Specification: Paragraph 7.1** UUV shall be capable of being transported, deployed/launched, operated, and recovered in sea states up to SS 3. SS shall be measured at the 40-foot curve. SS 3 is defined as wind velocity of 11-16 knots (KTs) with small waves 0.5m to 1.25m high, becoming longer; numerous whitecaps.(PMS 408, 2007)
18	What new technologies or techniques appear to be promising in reduction of the DTE sequence in the 10-40 foot depth range and why?	ALL	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:"Unmanned Cooperative Cueing and Intervention (UC2I: ONR project – Over-the Horizon project), Wi-Fi and autonomous launch and recovery platforms."

	Question	Directed at What Stakeholders	Answer
			Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011: MK 18 Mod 2 is showing promise for large area searches. It is showing that sensor integration is versatile; attempting to ensure it is open architecture. Mod 2 has greater duration than Mod 1. The key to success will be to ensure that the UUVs can reduce their false positive contacts to be equal or lower than the MMS. **Aamir Qaiyumi NSWC-PCD Interview 19 Aug -** Data fusion technology; if there are multiple capabilities available out there, focus should be made towards combining capabilities for enhanced performance. Limited attempts have been made to combine Forward Looking Sonar/Down Looking Sonar (FLS/DLS) with side scan sonar. Magnetic sensors should also be considered to be combined (help with buried mines).
19	Are there any environmental impacts concerns which need to be considered when developing a MCM system?	ALL	**Aamir Qaiyumi NSWC-PCD Interview 19 Aug -** High temp (heat concerns) Low frequency emissions are hurting marine life.
20	What are the required MTBF for a MCM system (Threshold & Objective)?	ALL	Stakeholders did not provide an answer to this question.
21	Is there any other similar effort trying to modify the existing systems to work in the 40ft zone?	PMS-420 ONR	**Admiral Williams (NPS)** PMS-420 group is researching the ability to use JABS in the VSW region.
22	In conducting MCM operation for an Amphibious Landing which would be considered more important speed or covertness? 1. If covertness is more important than speed; is it right to assume this mission will not be performed with AMCM assets? (The mission will	PMS-340 NMAWC	**USMC Capt Peter Moon -29 Aug E-Mail:**"Amphibious landings are dangerous enough without completely giving away the very valuable element of surprise. (This is verified as in a letter from CG MCCDC to CNO in 1999.)

	Question	Directed at What Stakeholders	Answer
	not be performed using an MH-60S) 2. If speed is more important, then are mammals or submarine launch UAV considered for use in performing MCM operations?		
23	In performing Amphibious Breach of Coastal Defense; what type of mine clearing operation is typically planned for: Mine Hunting or Mine Sweeping?	PMS-340 NMAWC	**Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011:** In training, the full DTE is exercised (mine-hunting).
24	According to Joint Publication 3-02, we understand that there are five phases to conducting an amphibious operation which are “Planning, Embarkation, Rehearsal, Movement, and Action” It is understood that MCM operation would commence with the planning operation. 1. However, at what phase would MCM Pre-assault operations start? (Embarkation, Rehearsal, Rehearsal, Movement?) 2. How much time would be typically allotted the MCM advance force to perform their mission?	PMS-340 NMAWC	Stakeholders did not provide an answer to this question.
25	In an Amphibious Operation a Boat Lane is described as having a length of 2000 to 2700 yards with a width of 500 yards (MCWP3-13, 2011)	PMS-340 NMAWC	**Danny Sinisi, PMA-299 OAMCM SEIT Lead** – “The current AMNS design would need to be modified to clear mines in the 10 to 40 ft VSW region.”
	a. In a typical Amphibious Operation		**USMC Capt Peter Moon -29 Aug E-Mail:"**12 lanes for 2 MEB

	Question	Directed at What Stakeholders	Answer
	involving 1 battalion; typically how many Boat Lanes will be planned?		sized element."
	b. Currently: how long does it take MCM operations to clear one boat lane?		**USMC Capt Peter Moon -29 Aug E-Mail "**Clearance objective for MCM operation is 48 hours from the start of overt operations with 72 hours being the threshold."
	c. Currently what types of assists are used to conduct MCM to clear a boat lane?		Stakeholders did not provide an answer to this question.
	d. Typically how much of the boat lane is considered in the VSW region?		Stakeholders did not provide an answer to this question.
26	In performing an Amphibious Operation that requires the penetration of a hostile environment that has anti-landing defense; will the priority of MCM be to: 1. Detect, Mark, and Avoid Mines? 2. Detect, Classify, Mark and Avoid Mines? 3. Detect, Classify, and Neutralize Mines?	PMS-340 NMAWC N852	**Matt Clements – (ITT Technical Representative EODMU1) Interview 8-29-2011**:"In real exercises #1 is the practiced answer. In training, we exercise 2 and 3, mission dependent"
27	How is a cleared lane marked for an amphibious force? Is there a preferred method to marking a lane that is cleared?		Stakeholders did not provide an answer to this question.

	Question	Directed at What Stakeholders	Answer
28	If the requirement is to perform Neutralization of Mines; at what time should the mines be neutralized? (It is assumed that to neutralize a mine it must be blown in place.) 1. Before Amphibious force crosses LD? If so – how much time before? 2. After 1st wave crosses the LD to secure surprise? 3. After all waves have reached the beach but support ships have not transitioned closure to the shore.	PMS-340 NMAWC N852	**Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011:** In practice, neutralization is not always done. Marking and avoidance is preferred. Neutralization is only done if necessary and if available.
29	In some of our reading, we have come across an AUV having chemical neutralization capability that provides a non-explosive neutralization ability (SEA Cohort 14, 2008). This would seem to promote an ability to covertly neutralize mines allowing the amphibious force intentions to go undetected. 1. Has there been some success in developing any of these systems? 2. Is there a desire by the US Navy to have this ability? 3. Are there limitations with this kind of a system?		**Danny Sinisi, PMA-299 OAMCM SEIT Lead** - ALMDS sweep cannot be done covertly.

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<tr><th></th><th>Question</th><th>Directed at What Stakeholders</th><th>Answer</th></tr>
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<tr><td>30</td><td>In NAVSEA 2009 to 2013 Strategic Business Plan, it shows the number ship types classified as Mine going from 14 in the year FY-08 to Zero in FY-20(NAVSEA Strategic Business Plan, 2009).
1. If this is this is still the current plan?
2. If this is still the current plan, what type of ships will be required to carry the MCM assets? In other words, is it envisioned the mission will be taken over by another ship or aircraft?
3. What C4I requirements are placed on the MCM assets to facilitate the ship to perform other missions?</td><td>NMAWC
N852
PMS-420
PEO LCS</td><td>LCDR John Schiller EODMU1 XO Interview 9-2-2011- The LCS is still a good concept. Although the MCM mission module is still not defined, there are a lot of unknowns out there that still are being worked out. Mission modules need to be reliable and capable of handling multiple threats. UMCM capability has been proven successful compared to some SMCM platforms.</td></tr>
<tr><td>31</td><td>Current Doctrine sites several limitations with deploy deploying Marine Mammal Systems (MMS) such as storage, transportation, water contamination (MCWP3-13, 2005). Would a MMS be used for an Amphibious Operation in a hostile environment? Is so when and how?
1. Prior to the beach landing?
2. After the beach landing?</td><td>NMAWC
PMS-408
N852</td><td>Bob Stitt - (ITT Technical Representative MMS Trainer / EODMU1), Mod 1NSWC-PCD interview 8-23-2011: Yes, MMS are still considered primary means of clearance. Although we train to complete the full DTE scenario, in practice this is not always done. In real world events, we detect, mark and avoid. UUVs are still in development and are not widely employed in practice. MK18 Mod 1 is the only UUV that has been used in operations. If time is a limiting factor then a method of AMCM will be the primary means to neutralization.</td></tr>
<tr><td>32</td><td>The LCS will be taking over the MCM</td><td></td><td>Stakeholders did not provide an answer to this question.</td></tr>
</table>

	Question	Directed at What Stakeholders	Answer
	mission in 2017 and the LCS concept is to have mission packages to configure the LCS to perform that mission. This poses a question for command and control. Who, for example, should have weapons release authority to destroy a mine, deploy MCM assets, or recover MCM assets – the ship's commanding officer or the officer in charge of the mission detachment (O'Rourke, 2011)?	NMAWC PMS 420 N852	
33	No other surface ships have been designed to operate as many off-board vehicles as the LCS. How will each ship coordinate its own off-board systems, including unmanned air, surface and underwater vehicles (O'Rourke, 2011)?	NMAWC PMS 420 N852	Stakeholders did not provide an answer to this question.
34	Should different ships take responsibility for particular dimensions –i.e. should one ship control all the underwater vehicles, or should that be left to each CO or OIC (O'Rourke, 2011)?	NMAWC PMS 420 N852	Stakeholders did not provide an answer to this question.
35	Is there any discussion for covertly deploying MCM Autonomous Underwater Vehicles (AUV) from Helicopters?	PMA-299 PMA-261	**Danny Sinisi, PMA-299 OAMCM SEIT Lead** – I don't know.
36	Is there any discussion for commanding and controlling AUVs from helicopter via a radio/IR link?	PMA-299 PMA-261	**Danny Sinisi, PMA-299 OAMCM SEIT Lead** – I have heard of commanding UAVs from the H-60, but not AUVs.

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APPENDIX C: COMPARISON TO GUADALCANAL

B. COMPARISON OF WWII AMPHIBIOUS FORCE WITH TODAY'S FORCE

On 7 August 1942, the first United States amphibious invasion of WWII took place on the islands of Guadalcanal, Tulagi, and Florida in the southern Solomon Islands as depicted in Figure 95.

Figure 95. WWII Guadalcanal Invasion

Depiction of the 7 Aug 1942 invasion routes taken by TF-62 during WWII (Friedman K. I., 2011; Miller Jr., 1948).

The US forces, Task force (TF) 44 and 62, consisted of cruisers, 15 destroyers, 3 fast transports, 5 Cargo Ships, 10 Troop Transports, 5 High Speed Minesweepers, 1 landing ship tank (LST), and 5 cargo transports. In addition to Task force 44, three aircraft carriers provided CAS for the invasion.

Table 37 lists the ships that were involved in the invasion. The main goal of the invasion was the capture of Henderson Field, an airstrip that had been built by the Japanese. The bombardment that was provided by the task force was so fierce that it deterred the defenders, and left the Marines to land unopposed.

Table 37. WWII Task Force 62 and Aircraft Carriers

Composition of WWII Task Force 62 and 44supporting the invasion of Guadalcanal 7 August 1942.

AIRCRAFT CARRIERS	Transports	CRUISERS	DESTROYER	Mine Sweeper
USS Saratoga	USS Little – Fast transport (APD) Transdiv 12 – Note (1) - Note (2)	USS Chicago Heavy Cruiser TF-62.2Sqdrn Yoke – Note (1), Note (2) , Note (3), Note (4)	USS Buchanan TF 62.4, Fire Group Mike – Note (1) Note (2) , Note (4)	USS Hopkins DMS-13 – Note (1)
USS Enterprise	USS Mckean – Fast transport (APD) Transdiv 12 – Note (1) - Note (2)	HMAS Australia Heavy Cruiser TF-62.2, Note (2), Note (3), Note (4)	USS Blue Destroyer Squadron 7 (DESRON 7), – Note (1) Note (2), Note (4)	USS Trever DMS-16 – Note (1)
USS Wasp	USS Gregory – Fast transport (APD) Transdiv 12 – Note (1) Note (2)	HMAS Hobart Light Cruiser TF-62.2, Note (2) , Note (3) , Note (4)	USS Henley DESRON 7, – Note (1), Note (2), Note (3), Note (4)	USS Zane DMS-14 – Note (1)
	USS Calhoun – Landing Ship Tank (LST) Transdiv 12 – Note (1) - Note (2)	USS Vincennes Heavy Cruiser TF-62.3, Note (2) , Note (4)	USS Helm DESRON 7, – Note (1) Note (2) , Note (3), Note (4)	USS Southard DMS-10 – Note (1)
	USS Athena - AKA-22 - Cargo Note (2)	USS San Juan Light Cruiser TF 62.4, Fire Group Mike – Note (1) Note (2) , Note (4)	USS Selfridge Destroyer Squadron 4, (DESRON-4), Note (2) , Note 4	USS Hovey DMS-11 – Note (1)
	USS Betelgeuse - AKA-260 - Cargo - Note (2)	USS Astoria Heavy Cruiser TF-62.3, Note (2) , Note (4)	USS Patterson – DESRON-4, Note (1) Note (2) , Note (3), Note (4)	
	USS Bellatrix -AKA-3 - Cargo - Note (2)	USS Canberra Heavy Cruiser TF-62.2,Sqdrn Yoke – Note (1) Note (2) , Note (4)	USS Bagley, DESRON 7, – Note (1) Note (2), Note(4)	
	USS Formahaut - Cargo - Note (2)	USS Quincy Heavy Cruiser TF-62.3,Note (2) , Note (4)	USS Ralph Talbot DESRON-4, Note (2), Note (4)	
	USS Libra -AKA-12 - Cargo - Note (2)		USS Mugford, DESRON-4, Note (2) , Note (4)	
	USS President Jackson APA-18 Transdiv Easy – Note (1) - Note (2)		USS Jarvis, DESRON-4, Note (2), Note (4)	
	USS Neville -APA-9 Transdiv Easy – Note (1) - Note (2)		USS Hull TF 62.3 Fire Support Group (FSG) L, Note (2), Note (4)	
	USS Zeilin APA-3 Transdiv Easy – Note		USS Dewey TF 62.3 FSG L, Note (2),	

AIRCRAFT CARRIERS	Transports	CRUISERS	DESTROYER	Mine Sweeper
	(1) - Note (2)		Note (4)	
	USS Heywood APA-6 Transdiv Easy – Note (1)		USS Ellet TF 62.3 FSG L, Note (2), Note (4)	
	USS Crescent City APA-21 - Note (2)		USS Wilson TF 62.3, Note (2) , Note (4)	
	USS President Hayes –APA-20 - Note (2)		USS Monssen TF 62.4, Fire Group Mike, – Note (1) Note (2)	
	USS President Adams -APA-19 - Note (2)			
	USS Hunter Liggett-AP-27 - Note (2)			
	USS American Legion -AP-35 - Note (2)			
	USS Barnett-APA-5 - Note (2)			

Note: (1) Information found in Task Force 62 Order to Action Tulagi-Guadalcanal -13 August 1942. FE24/A16-3 (CO1) - (Wilde Jr., 2001)
(2) (Friedman K. I., 2011)
(3) (Gill, 1968)
(4) (Budge, 2010)

If a similar invasion was to be attempted with present day forces, the invasion force would be made up of Task Force 76 (TF-76), Destroyer Squadron 31 (DESRON 31), and Carrier Strike Group 11 (CARSTRKGRU 11) as shown in Table 38. In this scenario, TF-76 was chosen because it is the US Seventh Fleet Expeditionary Strike group that is responsible for conducting expeditionary warfare operation in the Pacific (TF 76, 2011). Since TF-76 does not have any organic anti-surface or anti-subsurface assets and very limited anti-air capabilities, assumptions were made to designate DESRON 31 as an escort since it is a Pacific Fleet asset (COMDESRON 31, 2011). Therefore DESRON 31 priorities would be to protect TF-76 from air and surface delivered ASCM’s and subsurface torpedoes. DESRON 31’s secondary priority would be to provide suppression of coastal defenses. Carrier Strike Group Eleven (CARSTRKGRU 11) was also chosen for the scenario because it is also included in the 7th Fleet, which is assigned to the U.S. Pacific Fleet. CARSTRKGRU 11 is composed of USS Nimitz CVN-68, Carrier Air Wing Eleven (CVW-11) and Destroyer Squadron 23 (DESRON 23) (COMCARSTRKGRU ELEVEN, 2011). The total force would be composed of 1 aircraft carrier, 7 destroyers (DDG), 1 guided missile cruiser (CG), 4 Fast Frigates (FFG) 1 landing helicopter deck (LHD), 2 amphibious transport dock (LPD), 1 landing ship dock (LSD), 1 amphibious command ship (LCC) and 4 mine counter measure MCM ships.

Table 38. Today's Task Force 76, DESRON 31, and CARSTRKGRU 11

Table depicts composition of present day force needed for a Guadalcanal-type invasion mission (COMCARSTRKGRU ELEVEN, 2011; COMDESRON 31, 2011; TF 76, 2011).

CARSTRKGRU 11	AMPHIBIOUS TRANSPORTS TF 76	MCM SHIPS TF 76	DESRON 31
USS Nimitz (CVN 68)	USS Essex LHD-2	USS Avenger	USS Chafee DDG-90
USS Spruance (DDG 111)	USS Denver LPD	USS Defender	USS Chung-Hoon DDG-93
USS John Paul Jones (DDG 53)	USS Tortuga LPD	USS Guardian	USS Hopper DDG-70
USS William P Lawrence (DDG 110)	USS GermanTown LSD-42	USS Patriot	USS Paul Hamilton DDG-60
USS Sampson (DDG-102)	USS Blue Ridge LCC-19		USS Russell DDG-59
USS Vandegrift (FFG-48)			USS Crommelin FFG-37
USS Curts (FFG-38)			USS Reuben James FFG-57
USS Princeton CG 59			

This sets the stage to perform a comparison between a WWII task force and a today's force in providing suppression for MCM operation. To make a comparison we made the following assumptions:

1. Naval Fire Power to Support Amphibious Operation Assumptions

In calculating the fire power that was available for the WWII task force, the ships accompanying the aircraft carriers were not included. This is because the destroyers, cruisers, and battleship that protected the aircraft carriers were out of range to provide suppression fire for the landing force. However, the destroyers and cruiser accompanying the USS Nimitz could launch tomahawk missiles in support of the MCM operation and still protect the Nimitz with anti-air and anti-ship protection. Therefore these ships are used in the calculations of providing long range suppressive fire for an MCM operation. There are two variants of Tomahawk missiles: the RGM/UGM-109E Tomahawk Land Attack Missile (TLAM Block IV) and the RGM/UGM-109B Tomahawk Anti-Ship Missile (TASM), a radar guided anti-shipping variant (Sweetman, 2009).

Table 39 lists the firepower available to support the amphibious force.

Table 39. Fictional Modern Day Invasion Force Fire Power Mix

Depiction of modern day invasion force payload by support vessel.

SHIP	Vertical Launch Tubes	SM	ASROC	Harpoon	TASM	TLAM	5 Inch Gun	76 mm Gun
DESRON 31								
USS Chafee DDG-90	96	48	5		24	19	1	
USS Chung-Hoon DDG-93	96	48	5		24	19	1	
USS Crommelin FFG-37	40	30		10				1
USS Hopper DDG-70	90	45	5		23	17	1	
USS O'Kane DDG-77	90	45	5		23	17	1	
USS Paul Hamilton DDG-60	90	45	5		23	17	1	
USS Reuben James FFG-57	40	30		10				1
USS Russell DDG-59	90	45	5		23	17	1	
CARSTRKGRU 11								
USS Spruance DDG 111	96	48	5		24	19	1	
USS John Paul Jones (DDG 53)	90	45	5		23	17	1	
USS William P Lawrence DDG 110	96	48	5		24	19	1	
USS Sampson (DDG-102)	96	48	5		24	19	1	
USS Vandegrift FFG-48	40	30		10				1
USS Princeton CG-59	122	61	10		31	20	2	
	FIRE POWER AVAILABLE FOR SUPPRESSION					200	12	3

In calculating the fire power available the following assumption were made:

1. The 1st priority of the combat surface ships would be to counter the ASCM missile threat. Therefore half the available launch tubes would have Standard Missiles (SM).
2. The 2nd priority of the combat surface ships would be to counter any surface threats. Therefore half of the vertical launch tubes that are left from the total vertical launch tubes not containing SM would contain TASM.
3. Each combat surface ship would contain 5 to 10 ASROC torpedoes.

This would give the combined force the ability to launch 200 TLAMs in support of the Marine Amphibious force.

2. WWII and Modern Day Aircraft Assumptions and Comparisons

The second assumption was the number of planes used in support of Marine force during WWII was 91. The USS Saratoga could carry 91 aircraft (Friedman N. , 1983), the USS Wasp and USS Enterprise could carry 90 aircraft each (Friedman N. , 1983). However, not all these aircraft would be combat aircraft and not all of them would participate in providing air support. Therefore a conservative estimate of 90 aircraft was made to provide the Marines with CAS during the invasion. The aircraft that would have to provide CAS from the carriers would be the Navy Grumman F4F Wildcat fighter and the Navy Douglas SBD Dauntless (Scout/Dive Bomber). The F4F could provide close air-support with six 50 caliber machine guns (Writer, 2010). The SBD Dauntless could deliver one 1000 pound bomb and two 100 pound bombs in CAS (Dwyer, 2011).

It is unknown how many airplanes were deployed to support the Guadalcanal invasion; however, there were 103 SBD-3 Dauntless dive bombers and 173 F4F-4 Wildcats fighters that were available from the carrier force to support the invasion of Guadalcanal. Not all aircraft were dedicated to support the invasion; instead, there was a percentage to provide combat air patrol (CAP) for carriers a quick response for Anti-Ship operations. If 75% of the SBD-3 dive bombers and 50% F4F fighters were dedicated to support the invasion, this would give the amphibious force 77 dive bombers and 87 Fighters for CAS.

Therefore, a ground support attack could include a mix of 77 Dauntless and 87 Wildcats. This would give the support attack the ability to deliver 92,400 lbs of ordnance with aircraft machinegun support in one mission.

Table 40 shows the number and type of aircraft that was available aboard the carriers to support the invasion.

Table 40. WWII Carrier Task Force TF-61

Table shows the available aircraft on the WWII carriers to support the invasion of Guadalcanal (Budge, 2010).

Carrier and Squadron		**Number of Aircraft**	**Type of Aircraft**
CV Saratorga			
	VF-5	34	F4F-4 Wildcat
	VB-3	19	SBD-3 Dauntless
	VS-3	18	SBD-3 Dauntless
	VT-8	16	TBF-1 Avenger
CV Enterprise			
	VF-6	36	F4F-4 Wildcat
	VB-6	18	SBD-3 Dauntless
	VS-5	18	SBD-3 Dauntless
	VT-3	15	TBF-1 Avenger
CV Wasp			
	VF-71	29	F4F-4 Wildcat
	VS-71	15	SBD-3 Dauntless
	VS-72	15	SBD-3 Dauntless
	VT-7	10	TBF-1 Avenger

In comparison, the modern day Nimitz aircraft carrier typical aircraft load-out includes 12 FA-18E/Fs, 36 FA-18s, 4 EA-6B, 4 E-2C, 4 SH-60F, and 2 HH-60H aircraft (Nimitz Class, 2011). If 12 FA-18s were dedicated to providing CAP for the Nimitz; this would leave 40 aircraft (12 FA-18E/F, 24 FA-18C/Ds and 4 EA-6Bs) for providing CAS to the Marines. Note that the EA-6Bs would provide the electronic attack part of the obscuration mission.

Each FA-18C/D can deliver up to 13,700 lbs of stores to include, free falling or guided bombs, cluster bombs, or napalm tanks (Boeing, 2011). In addition to the aircraft from the Nimitz, the LHD can provide 6 Harriers AV-8B and 4 Super Cobras to provide suppression for the MCM operation (Nimitz Class, 2011). The AV-8B can provide 13,200 lbs of stores to also include cluster bombs, guided and unguided bombs and napalm canisters (Donald & March, 2004). The Super Cobra can carry up to seventy 2.75-inch rockets or eight 5-inch rockets or 8 Hellfire missiles (AH-1W / AH-1Z Super Cobra, 2011). For this example, it estimated that the present day forces can deliver 627,200 lbs and 280 2.75” rockets in support of the MCM mission.

3. Firepower Comparison

Table 41 tabulates the fire power that could be used for suppression, obscuration and Isolation during an MCM operation between both today's and the WWII force. The modern day naval air force can deliver 7 times more ordnance faster and more precisely than the WWII force with fewer planes. The US Navy and Marine Corps depend on the naval CAS to provide the bulk of the suppression and obscuration for the MCM operation. However, if air power parity exists as it did in WWII, or the enemy gains air superiority, it is envisioned that fewer planes would be released to support the MCM operation. Additionally planes may not be able to loiter without air superiority to seek targets of opportunity. In this situation, they will not be able to sustain consistent suppression of targets.

Table 41. Fire Power for Suppression Comparison between WWII with Today

Comparison of suppression fire available to WWII and present day forces supporting an amphibious landing.

WWII TF 44 SUPPRESION FIRE POWER			**TODAY SUPPRESSION FIRE POWER**	
Number Guns	Gun Type		Number Guns/Rockets	Guns/Rockets Type
42	8 inch Guns		200	UGM-109ETLAM
20	6 inch Guns			
123	5 Inch Guns		12	5 Inch Guns
39	4 Inch Guns		3	76 mm
17	3 Inch Guns			
16	1 Inch Guns			
52	40 mm			
2	37 mm		10	25 mm
42	20 mm		5	20 mm
Naval Combat Aircraft			Naval Combat Aircraft	
164			50	
92,400 lbs	Ordnance in Mission		627,200 lbs	Ordnance in Mission
			280	2.75 Rockets in Mission

The WWII Naval force produced more sustained fire power from their ships upon an objective than a modern day force would. This is because the WWII era ships could sustain a land barrage. Clearly it can be seen that a WWII task force can provide more effective suppression and obscuration fire than a modern day task force by the sheer number of artillery pieces at its disposal. An argument can be made that Tomahawk missiles and laser guided munitions' from modern day aircraft can be more precise in their attack to eliminate coastal defenses. However, the assumption is that the amphibious force can accurately identify the over watched positions or the land based defense artillery and mortars. This might not be the case with an island that has a jungle environment with well-prepared defensive positions. However,

suppression fire does not need to be accurate. It needs to be close enough to create confusion, fear, and obscuration of the target to be effective. Consider if just 10 rounds from each 8, 6, 5, and 4 inch WWII gun were used in suppression; it would total 2040 rounds for suppression as compared to 200 TLAM.

4. WWII and Current Operations Breaching Comparison

Figure 96 graphically summarizes the MCM Breaching capabilities between the WWII force and the US Naval force of today. In short, the present day US Naval force has fewer capabilities to provide suppression and obscuration for mine obstacle breaching operation when the US does not have air-superiority. The WWII force could move further close to the beach and provide suppressive and protective fire power for the MCM force and thus provide Isolation and Security. Today's forces can quickly land Marine forces by air to provide forces that can isolate and harass the coastal defense and thus provide "Isolation" and Security for the MCM force. Therefore, due to these unique aspects both the WWII and present day forces have equal capabilities to isolate the mine obstacle. However, the mine obstacle sweeping capability of the modern day MCM ships are superior to the WWII force, but not by much. Today's force has greater capability to detect and find the mines, but the MCM reduction capabilities of today still depend on men (divers) to neutralize the mines like the WWII force.

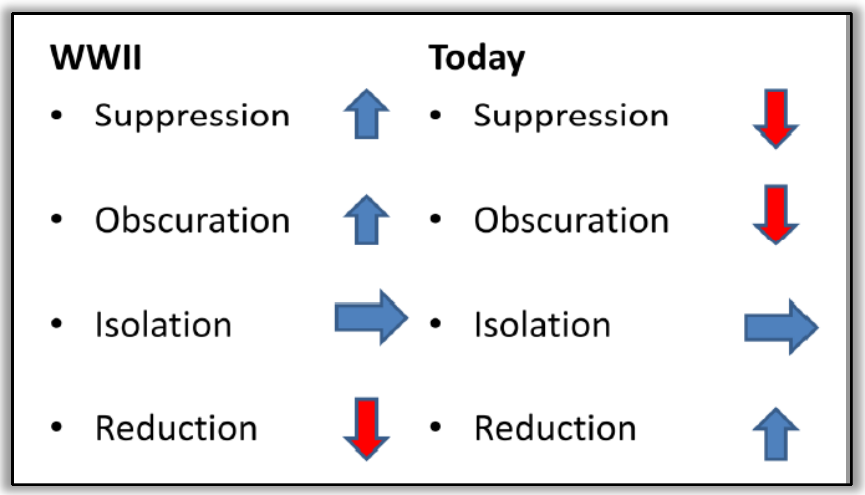

Figure 96. Amphibious Mine Breaching Comparison between WWII and Today

Figure provides a comparison of capability of the amphibious assault forces for MCM between WWII and present day.

C. COMPARISON OF WWII AMPHIBIOUS FORCE WITH FUTURE AMPHIBIOUS FORCE

To make a comparison of mine breaching capabilities with future assets, assumptions for the composition of a future force shown in Table 42 were developed using assets that will be available 15 years from now. It was assumed that the future force would be composed of1 aircraft carrier, 8 destroyers (DDG), 2 guided missile cruiser (CG), 1 Amphibious Assault ship (LHA), 2 amphibious transport dock (LPD), 1 mobile landing platform (MLP), 1 Joint High Speed Vessel (JHSV) and 4 Littoral Combat ships (LCS).

Table 42. Future Task Force and CSG Supporting Amphibious Operation

Composition of potential future force to support an amphibious landing.

AIRCRAFT CARRIERS	AMPHIBIOUS TRANSPORTS	LITTORAL COMBAT SHIPS MCM	Cruiser Destroy Squadron
USS Nimitz CVN	USS America LHA-6	USS Freedom LCS	USS Port Royal (CG 73)
USS Spruance (DDG 111)	USS New York LPD	USS Independence LCS	USS Chafee DDG-90
USS John Paul Jones (DDG 53)	USS Arlington LPD	USS Fort Worth LCS	USS Chung-Hoon DDG-93
USS William P Lawrence (DDG 110)	USS (Not Designated) MLP	USS Coronado LCS	William P. Lawrence (DDG 110)
USS Sampson (DDG-102)	USS Spearhead JHSV		USS Zumwalt (DDG 1000)
USS Gravely (DDG 107)			Michael Monsoor (DDG 1001)
USS Princeton CG 59			

Table 43 and Table 44 show the calculations for the suppressive fire power of a future force as compared to the WWII force.

Table 43. Future Invasion Force Fire Power Mix Available For Suppression

Tabulation of future force firepower capabilities to support an amphibious landing.

SHIP	Vertical Launch Tubes	SM	ASROC	TASM	TLAM	155 mm Gun	5" Gun	57 mm
CGDESON XX								
USS Port Royal (CG 73)	122	61	10	31	20		2	
USS Chafee DDG-90	96	48	5	24	19		1	
USS Chung-Hoon DDG-93	96	48	5	24	19		1	
Wayne E. Meyer (DDG 108)	96	48	5	24	19		1	
USS Zumwalt (DDG 1000)	80	45	5	23	17	2		
Michael Monsoor (DDG 1001)	80	45	5	23	17	2		
CARSTRKGRU 11								
USS Spruance DDG 111	96	48	5	24	19		NOTE 1	
USS John Paul Jones (DDG 53)	90	45	5	23	17		NOTE 1	
USS William P Lawrence (DDG 110)	96	48	5	24	19		NOTE 1	
USS Sampson (DDG-102)	96	48	5	24	19		NOTE 1	
USS Princeton CG-59	122	61	10	31	20		NOTE 1	
TF-XX								
USS Freedom LCS								1
USS Independence LCS								1
USS Fort Worth LCS								1
USS Coronado LCS								1
FIRE POWER AVAILABLE FOR SUPPRESSION					**201**	**4**	**5**	**4**

Note 1: These destroyers and cruisers have 5 inch guns but would be too far away to use them in the suppression mission for an obstacle breech. Therefore, they are not included in the calculation for providing suppression support.

Table 44. Fire Power for Suppression Comparison between WWII with Future

Comparison of suppression fire available to WWII and future forces supporting an amphibious landing.

WW II TF 44 SUPPRESION FIRE POWER			**FUTURE SUPPRESSION FIRE POWER**	
Number Guns	Gun Type		Number Guns/Rockets	Guns/Rockets Type
42	8 inch Guns		201	UGM-109ETLAM
20	6 inch Guns		4	155 mm
123	5 Inch Guns		5	5 Inch Guns
19	4 Inch Guns		4	57 mm
12	3 Inch Guns			
16	1 Inch Guns			
52	40 mm			
2	37 mm		10	25 mm
42	20 mm		5	20 mm
Naval Combat Aircraft			Naval Combat Aircraft	
164			50	
92,400 lbs	Ordnance in Mission		627200 lbs	Ordnance in Mission
			280	2.75 Rockets in Mission

The future force has a significant increased suppressive fire power over the present day to force. The LCS carries 880 rounds of 57 mm and the Zumwalt class destroyers can carry up to 950 rounds of 155mm. It is projected that the 155 mm guns will have a maximum range of 62 miles. If these ships can be used in a suppressive fire mode, they could possible sustain fire up to 5420 rounds. This is close to parity with the WWII task force.

D. NEED FOR OTH CAPABILITY

What offsets the task force from providing close in suppression for the MCM force is the protection of the amphibious ships from ASCM. The presence of ASCM's drives the requirement for the ATF to operate from OTH. OTH is difficult term to define and as the definition of distance varies to what an appropriate OTH standoff distance is from the objective. Joint Publication 3-02 Amphibious Operations states that "over-the-horizon amphibious operation is an amphibious operation initiated from beyond visual and radar range of the enemy shore." (JP 3-02, 2009). This is normally at the horizon which is approximately 22 to 25 miles at sea. However, based on the analysis of being able to react to ASCMs it is suggested that the AFT contain MCM assets that initially operate no closer than 50nm from the objective. Additionally, other analysts have said that amphibious assaults will be launched from OTH at 25

to 50 miles at sea (Committee on Naval Expeditionary Logistics, 1999). This further justifies that current and future MCM system should have the ability to be deployed and launched from distances greater than 50 nm.

In a report to congress, the Expeditionary Fighting Vehicle (EFV) was criticized for being designed to be launched from 25 miles from the shore (Feicket, 2010). The report pointed out that this was not far enough by citing an example of a 2006 incident in which a Hezbollah C-802 cruise missile successfully attacked an Egyptian ship 36 miles from shore (Eshel, 2006). The Chinese and Russians have developed sea skimming ASCM that travel at speeds over Mach 2. The Russian P-800 NATO designation SS-N-22 can travel at Mach 2.3 for over 186 miles (Russian/Soviet Soviet Sea-Baseed Anti-Ship Missiles, 2005). These missiles can be launched from ships, submarines, aircraft, and truck mounted launchers. If launched at the amphibious force, it is estimated that the ships will have approximately 35 seconds to react to it when detected at the maximum detection range of the ships. Reaction time can easily be equated to probability of survival. If the amphibious force is any closer to the launch point of origin, it decreases the anti-ASCM reaction time for the amphibious force. The most likely point of origin for the ASCMs will be from concealed camouflaged areas around the objective or from submerged submarines. In the projection of force for Guadalcanal example, covered and concealed ASCMs will be either on Guadalcanal or one of the nearby islands. If the ATF cannot provide sufficient suppression fire to Guadalcanal or the nearby islands to protect the MCM operation or the ATF from ASCMs, it drives the requirement to operate at a safe distance from OTH to Guadalcanal and its surrounding islands.

If the ATF operates more than 50 nm from the objective this reduces the suppressive fire support coming from the LCS. Once again the WWII force appears to be superior in providing suppression and obscuration for the MCM operation. If the MCM operation cannot depend on being provided with sufficient suppression of coastal defenses and obscuration from hostile forces, this becomes a gap in the performance of conducting MCM Operations. This establishes the need for MCM operations to be done covertly.

There are more reasons the MCM system need to have the capabilities to operate covertly other than the inability to have suppressive fire. According to the Navy concept of "Ship-to-Objective-Movement (STOM)", it calls for an emphasis in the need for clandestine efforts to determine enemy strengths and weakness by locating and identifying mines and obstacles (Marine Corps Development Command, 2011). STOM relies on surprise to achieve amphibious assaults from OTH. As stated in the Marine Corps STOM concept document:

"The enemy will contest the control of air, maritime, land, space, and cyberspace domains. Amphibious forces will offset these challenges by remaining, at least initially, over the

horizon, using the expanded maneuver space offered by the sea to complicate enemy targeting and provide more reaction time to defeat counterstrikes. From this tactically advantageous position, the landing force will be able to initially avoid enemy strength, maneuver to create multiple entry points and disrupt enemy anti-access strategy and then overwhelm adversary defenses to attack or influence its' landward objectives" (Marine Corps Development Command, 2011).

The STOM concept does change the tactics for breach obstacles. In other words, mine obstacles and gaps in the defense must be identified covertly without the use of suppressive fire. This must be done to maximize the effect of a surprise attack. Additionally, the Navy identifies in the STOM concept paper, "…breaching, preparatory fires, and obstacle clearing which were traditionally pre-assault tasks, will become an integral part of the assault phase" (Marine Corps Development Command, 2011). This drives the need for a MCM capability to locate, assess, classify, identify gaps, and map the mine field and obstacles before the assault. This in turn drives a need for the MCM system to communicate this information back to the TF before the assault so that commander can make assessments and plan for entry points. In order to plan for entry points, this drives a need for the TF to have a capability to communicate with MCM system the desired entry points and boat lanes to the MCM systems after the assessment of the reconnaissance. Lastly creates a need for the MCM systems to reacquire the desired mines for neutralization and to synchronize the neutralization with the assault or to neutralize the mines covertly before the assault.

APPENDIX D: LEVELS OF AUTONOMY DISCUSSION

This appendix supplements the discussion of levels of autonomy in the main report, providing further detail on each level of autonomy and the solution architectures to support the level.

A. FULLY AND SEMI AUTONOMOUS OPERATIONS

NIST defines fully autonomous as:

> A mode of operation of an UMS wherein the UMS is expected to accomplish its mission, within a defined scope, without human intervention. Note that a team of UMSs may be fully autonomous while the individual team members may not be due to the needs to coordinate during the execution of team missions (NIST, 2004).

A system which deploys fully autonomous vehicles has a human operating in a supervisory control mode, and vehicles operating as intelligent agents who also can operate in a supervisory capacity. Supervisory Control is a mode where one or more human operators are intermittently sending and receiving information to the unmanned system (Hew, 2010). It is where a machine closes a control loop, and a supervisor intermittently programs the machine with changes in mission. An intelligent agent is an autonomous entity that observes and acts upon an environment directing its activity towards achieving goals (Hew, 2010).

A supervisor is an agent that has supervisory control over subordinate agent(s) and can be human or artificial without restriction (Hew, 2010). A supervisor intermittently reprograms its subordinates, using information that it has gathered from the environment or taken from the subordinate agents (Hew, 2010). The supervisor monitors mission progress, provides mission level directions, and coordinates missions (NIST, 2004).

In a fully autonomous condition, a single human operating in supervisory control can direct the operation of one or several vehicles in an MCM operation. This means that the human would have a tactical display maintaining situational awareness of the overall status of vehicles, the mode they are operating in, their status, the reported locations of mines and obstacles, and the overall status of routes reconnoitered and cleared. The human controller would be able to reprogram one vehicle or a group of MCM vehicles for mission changes, select routes for clearance, and grant permission for neutralization.

It is envisioned that the vehicles operating as intelligent agents have on-board processing for self-navigating, target detection, target classification, obstacle avoidance, mapping the AO, and communicating.

It is also envisioned that one of the vehicles can operate as supervisor of one or more of the other MCM vehicles in the AO to change search patterns or redirect searches. This means that the supervisor not only has situational awareness of its environment, but also the environment and status of its intelligent agents.

The main characteristic of fully autonomous operation is that the human needs only very limited intermittent communication with one or more of the vehicles. Because of this, the bandwidth of the communications between the human and vehicles and between vehicles in the field can be very limited.

Another characteristic of fully autonomous operation is that the vehicles must maintain redundancy in critical sensors for navigation and processing. The navigation solution is critical for determining vehicle location, mine location, performing obstacle avoidance, maintaining search patterns, and performing collaborated missions with other vehicles. The navigation solution must be highly reliable and accurate to perform these functions over long periods of time. The vehicle must have redundancy in the navigation sensors in order compensate for errors caused by degradation or failures in sensor inputs. It must be able to compare navigation solutions to correct errors in drift and to maintain a reliable accurate navigation solution for long periods of time.

The vehicles must be able fuse information that comes from different sensors for the purpose of target classification. Fusion is the process of combining or blending of relevant data and information from single or multiple sources into representation formats to support the interpretation of the data and information and to support system goals like recognition, tracking, situation assessment, sensor management, or system control. It involves the process of acquisition, filtering, correlation, integration, comparison, evaluation and related activities to ensure proper correlations of data or information exist and draws out the significance of those correlations (NIST, 2004). It is envisioned that the MCM system has level 4 or level 5 data fusion. These levels of fusion are described in the NIST Special Publication 1011. Level 4 data fusion consists of assessing the entire process and related activities to improve the timeliness, relevance and accuracy of information and/or intelligence. It reviews the performance of sensors and collectors, as well as analysts, information management systems, and staffs involved in the fusion process (NIST, 2004). Level 5 fusion connects the user to the rest of the fusion process so

that the user can visualize the fusion products and generate feedback/control to enhance/improve these products (NIST, 2004).

A fully autonomous vehicle can have several advantages for covert operations in that it can be planted in the AO long before it is needed. A fully autonomous vehicle could lie dormant for several months until it is activated to perform its mission by a predefined signal or time period. This could give advantages to seeding the vehicles in the AO by various clandestine methods. Additionally it is anticipated that autonomous vehicles have higher development cost, but much lower life cycle cost due to the fact the fully autonomous vehicles need fewer people to operate and control them.

There are a minimum of 3 redundant critical sensors that are measured independently to enable fully autonomous operation. This is done so that critical information can be compared for sensor errors due to degradation and failures. These critical sensors are pressure transducers used to measure depth and speed. It is also recommended to that the system contain 3 redundant inertial reference systems and 3 independent processors to insure precise navigation.

B. TELE-OPERATED SYSTEM

Tele-operation is where a human operator, using video feedback and/or other sensory feedback, either directly controls the actuators or assigns incremental goals, waypoints in mobility situations, on a continuous basis, from off the vehicle via a tethered or radio linked control device. In this operation mode, the UMS may take limited initiative in reaching the assigned incremental goals (NIST, 2004).

Tele-operated MCM vehicles have very limited SA because of limited onboard processing and lack in redundancies for critical sensors. The MCM vehicles have level 1 or level 0 fusion abilities. Level 1 fusion is where a vehicle takes a new input and normalizes the input data, correlates the data into an existing entity database, and updates that database.

Tele-operated vehicles need to be recovered to perform post mission analysis or need to continuously stream data back to the MCM control ship for mission processing. The human operator needs continuous communication with the vehicle to assess and direct its operation. The operators per shift could range from 1 to 2 personnel to operate one vehicle.

The vehicle cannot be planted covertly and expected to lie dormant without the risk of losing the vehicle due to very limited SA.

It is envisioned that the MCM vehicles would be able to operate in this mode when all or most of it critical sensors used for navigation have failed or been severely degraded or its ability to process navigation inputs or sensor inputs has been severely degraded.

C. REMOTELY PILOTED SYSTEM

Remotely piloted systems are where a human operator, without benefit of video or other sensory feedback, directly controls the actuators of the UMS on a continuous basis, from off the vehicle and via a tethered or radio linked control device using visual line-of sight cues. In this mode, the UMS takes no initiative and relies on continuous or nearly continuous input from the user (NIST, 2004).

This mode of operation requires an operator to have direct sight of the MCM vehicle. This can be accomplished from video provided by another platform, or by an operator controlling the vehicle while maintaining eyes on the vehicle.

In the case for MCM operations, the assumption would be that humans would be conducting PMA at the control ship.

Remotely piloted systems have no situational awareness of their environment, and require constant operator input to guide it to accomplish its mission.

It is envisioned that the MCM vehicles should be able to operate in this mode when all or most of its critical sensors used for navigation have failed, or its ability to process navigation inputs are failed and its sensor inputs has been severely degraded.

D. ADDITIONAL AUTONOMY ARCHITECTURE CONSIDERATIONS

Additional features such as processing capability, neutralization responsibility, sensor confirmation, DTE time delay activation, requirements for doctrinal change, manning recommendations, real-time communication requirements, and Post Mission Analysis requirements need further consideration compared to the system level of autonomy:

1. Processing Capability: As autonomy increases, the processing capability increases. As the decision control shifts from the human to the system with increasing autonomy, the system needs to have the processing capability to handle complex behavior and decision algorithms.
2. Neutralization Responsibility: Increasing autonomy allows the system to take responsibility for DTE completion. A concept would be that as autonomy

increases, the system would be authorized to engage the mine if it identifies a target within specific parameters without waiting for the human to make decisions.

3. Sensor Confirmation: With the human in the loop at the lower levels of system autonomy, the system would be required to show the human target confirmation using only one of four sensors. This would allow the human to make decisions on the target even if there is only one sensor to confirm data. At higher levels of autonomy, the system would need additional target confirmation data since the human is absent from the loop as a monitor.
4. DTE time delay activation: A concept benefit with highly automated systems is that it would have the capability to activate a search on either a time delay or upon human confirmation. This allows the vehicle to be seeded in the AO and lie dormant until it is needed. This allows the vehicle to be planted covertly and reactivated at a later time.
5. Requirements for Doctrinal Change: As defined in the NWP MCM 3-15 doctrine, target neutralization can only be executed after visual identification is made by a diver. Not only does this keep the human diver in harm's way, it is not matching the scope of current roadmap doctrinal concepts. The doctrine should be in line with allowing the system to provide identification details as autonomy is increased.
6. Manning for the system: As the level of autonomy increases to a fully autonomous system, the number of operators that are needed to control and oversee the system will decrease substantially.
7. Post Mission Analysis: Increasing autonomy in conjunction with establishing a real communication network allows the system to take on the responsibilities of the DTE sequence with human monitoring. This in turn allows real-time processing and decision making at the higher levels of autonomy and post mission analysis would no longer be required.

E. COMMUNICATION LEVELS

An important consideration is the methods of communications that are used for system operation. The system's level of autonomy plays a significant factor in how much data is needed to be transmitted and received. Systems with the higher levels of autonomy only need general instructions from the operator, such as the dimensions of the search area, where systems with more human interaction need to transmit information much more often. Table 45 highlights the frequency of communications for each level of autonomy.

Fully autonomous systems should have the ability to transmit its location and status periodically to the systems oversight personnel. These updates are transmitted on an intermittent or periodic basis. Location and function updates would be transmitted at a regular time interval with possible mine locations and neutralizations sent back to the oversight as needed.

With the remotely piloted option, communications would occur in a continuous manner. This would mean command and control data and sensor feeds would be transmitted from the SPUDS to a local operator. This would require a much higher bandwidth than only sending periodic updates.

Table 45. Communication Exchange Frequency by Autonomy Level

This table shows the frequency of communications by each autonomy level. The fully autonomous system will provide only intermittent updates, while the remotely piloted option provides a continuous feed from the sensors.

	Frequency of Communications
Fully Autonomous	intermittent
Tele-operated	semi continuous
Remote Piloted	continuous
MK 18 UUV	semi continuous (C2 data only)

One of the most difficult tasks that must be performed in MCM operations for the amphibious force is establishing OTH communications between the MCM vehicles the MCM control ship. Additionally, establishing underwater communications in the noisy VSW environment is also difficult. There are three basic architectures that are considered for this project. The first architecture consists of a series of buoys that use Wi-Fi communication to transmit information. This is used with fully autonomous vehicles. The second architecture uses

directional line of sight communication to transmit data back to the command center via an airborne data link. This architecture would force an antenna to be tethered to a surface above the water to transmit and receive data. The last architecture uses a local operator to command and control the vehicle. This also requires an antenna to be tethered to a surface above the water to transmit and receive data. Table 46 provides details of viable communication systems for each level of autonomy.

Table 46. Communication Comparison for Autonomy Levels.

This table provides the details around the two potential communications architectures for the SPUDS. The chart depicts pros and cons involved with the two architectures.

Levels of Autonomy	Communications Setup	Bandwidth Ability	Vehicle Antenna Above surface	Communications Method	Surface time of antenna
	Type	*H/M/L*	*Y/N*	*Type*	*Time*
Fully Autonomous	Wi-Fi/Buoy (Disposable)	M	N	RF (UHF/SHF)	Not Needed - Radio Backup Communication
Tele-Operated	Data-link using Airborne Platform	H	Y	SHF/EHF	Constant
Remote Control	Light of Sight with Local Operator	M	Y	VHF/UHF	Constant

F. CURRENT AUTONOMY LEVELS

An initial analysis has been conducted on the MK 18 Mod 1 UUV system, divers and MMS, to identify current system level of autonomy. Taking the understanding of the current operating and fielded systems, the intent of defining autonomy architectures was to take each definition of autonomy and identify which system features would be necessary to meet the definition.

1. Diver Operations

Current MCM operations using divers put a large burden on humans performing clearance operations, putting humans at risk in hostile and dangerous environments, obligating the human to perform all functions of the DTE. Although this has been the approved method for MCM clearance operations since the 1950’s, technology developments and OPNAV future concepts have been encouraging the removal of the human and increasing the reliance on unmanned systems to complete the tasking. Understanding the level of tasking that is placed on humans is important to understand in order to start identifying methods of reducing their

burdens. An important area to note where OPNAV future concepts need to shift doctrinal procedures is within the NWP MCM 3-15. Current doctrine states that a target can only be neutralized once a human has visually identified (Vid) and classified the target. Table 47 shows the functions that are currently performed by a human diver compared to a system in MCM operations.

Table 47. Current MCM Diver System Functions

This table shows the functions that are performed by the human diver in MCM operations. In this case, the human carries out the entire detect to engage sequence.

DIVERS		
Functions	Human Task	System Task
Search	x	N/A
Detect	x	N/A
Identify	x	N/A
Classify	x	N/A
Engage	x	N/A
Communication	x	Team Leader with Host Platform

2. MMS Operations

MMS operations are similar to divers in that a large burden is put on mammals. Although mammals have an increased search area capability over divers, humans still must remain close to operational areas in order to support the mammal. During MMS operations, divers are still required to visual identify a target before neutralization is authorized. Table 48 provides an overview of functions that are carried out by mammals and humans in an MCM operation.

Table 48. Overview of MMS Operations

This table depicts functions that are carried out by the mammal vs. a human being. As shown, the human tasks are mostly verification to marine mammal's findings.

MMS		
Functions	Mammal Task	Human Task
Search	x	N/A
Detect	x	N/A
Identify	x	Verify
Classify	x	Verify
Engage	x	Verify
Communication	x	X

3. MK 18 Mod 1 UUV

The MK 18 Mod 1 UUV is a sensor platform where raw data is collected. There currently is no real time data transmit capability with some limited C^2 information that can be communicated via acoustic communication nodes to the UUV during operations. Human operators must retrieve the vehicle, download raw data, and convert into imagery data that can be viewed by Post Mission Analysis (PMA) Operators. It is also important to note that Probability of Detection/Probability of Classification (P_dP_c) is not based on MK 18 UUV's capability, but is based the human's ability to interpret imagery data from raw sensor data. This has proven challenging to accurately measure P_dP_c since the values can vary and are directly related to the capability of the trained operator.

Current operations have shown that one hour of UUV mission data yields approximately one hour of PMA Operators reviewing imagery. Using humans to identify targets has proven somewhat successful, but involves intense training and man-hours to prepare humans to complete this task well. There are currently no fielded elements that assist the operator in identifying targets. Table 49 provides an overview of the functions performed by humans and the MK 18 UUV in an MCM mission.

Table 49. Summary of Human and System Tasks for the MK 18 Mod 1

This table provides an overview of the functions that are currently completed by a human vs. system for the MK 8 Mod 1 UUV.

MK 18 Mod 1 UUV		
Functions	Human Task	System Task
Search		x
Detect	x	
Identify	x	
Classify	x	
Engage	x	N/A
Communication	x	x

4. Other Considerations

As mentioned, current doctrine requires visual identification by a human before neutralization. If the intent is for autonomous technology in the future development to remove the burden, technology must first be proven mature and accurate. Additionally, the MCM community would need to modify doctrine concepts to allow systems to be considered a valid identification and classification platform.

As noted, Probability of Detection/Probability of Classification (P_dP_c) value is not based on MK 18 UUV's capability, but is based the human's ability to interpret imagery data from raw sensor data. Not only would a doctrinal change be necessary to enable systems to identify and classify targets, but software and autonomy behavior would need to be developed to support this. Enabling the shift of limited human tasking and elevating technology and completing the DTE functions using autonomous systems would allow the P_dP_c values to be based on measurable, comparable technology performance.

APPENDIX E: DETAILED ARCHITECTURE MAPPING

A. ALTERNATIVE ONE MAPPING

1. Alternative One Components Mapped to Functions

Table 50 summarizes how each component addresses the functions explored in this report (search, detect, identify, engage, and communicate). Table 50 also shows the breakout of tasking that is performed by human operators, the MCM ship, and the SPUDS for Alternative One.

Table 50. Alternative One Functions Allocated to System Components

This table depicts functions allocated to the Advanced MCM system for Alternative One.

Top Level Function	1st Level Sub function	Performing System			
		Human/Host Platform		MCM Vehicle	OTH Communication
		Human	Sub Component	Sub Component	Sub Component
Search FS7.	Enter operational area FS.7.1	Mission Operator or Tactical Oversight query vehicle status	Mission Operator & Tactical Oversight Computers, Vehicle/Tactical Displays	Propulsion System	GPS/Acoustic Navigation Beacon
				MSN Processor	
				INS/GPS(3)	
			Server	DVL	Acoustic/Wifi
			Recorder/Playback	Depth/Pressure Sensor	
			Wi-Fi radio	Acoustic Comm	
	Activate search sensors FS.7.2	.		Optical Sensor (4) Optical Sensors	
				Magnetic Sensor System Deploy Magnetic Gradiometer	
				Sonar Sensor System (1)	
				Power System	
	Follow search commands FS.7.3			Power System	GPS/Acoustic Navigation Beacon
				INS/GPS (3)	
				DVL	
				Propulsion System	Acoustic/Wi-Fi
				Mission Processor(3)	
				Pressure Depth/Temperature Transducers	
				Acoustic Comm	
	Record platform location FS.7.4			INS/GPS(3)	GPS/Acoustic Navigation Beacon
				DVL	
				Mission Processor(3)	
				Pressure Depth Sensor	
				Acoustic Comm	

Top Level Function	1st Level Sub function	Performing System			
		Human/Host Platform		MCM Vehicle	OTH Communication
		Human	Sub Component	Sub Component	Sub Component
	Create mission complete message FS.7.5	Mission Operator or Tactical Oversight query vehicle status.	Server	INS/GPS(3)	GPS/Acoustic Navigation Beacon
			Recorder/Playback	DVL	
			Mission Operator Computers Status Display/Controls	Mission Processor(3)	
			Tactical Oversight Computer and tactical map Display/Controls	Pressure Depth Sensor	
			Wi-Fi Radio	Acoustic Comm	Acoustic/Wi-Fi
	Deactivate search sensors FS.7.6			Optical Sensor	
				Magnetic Sensor System	
				Sonar Sensor System	
				Mission Processor	
				Power System	
Detect FD.1	Receive information from sensors indicating contact in the area FD.1.1			Optical Sensor	
				Magnetic Sensor System	
				Recording System	
				Sonar Sensor System	
				Mission Processor(3)	
	Record location of contact FD.1.2			Mission Processor(3)	
				Recorder	

Top Level Function	1st Level Sub function	Performing System: Human/Host Platform — Human	Performing System: Human/Host Platform — Sub Component	Performing System: MCM Vehicle — Sub Component	Performing System: OTH Communication — Sub Component
	Record environmental information from sensors FD.1.3			Pressure Sensor(3)	
				Temperature Sensor(3)	
				Mission Processor(3)	
	Create message about a detection in the area and its location FD.1.4	Mission Operator or Tactical Oversight query vehicle status. - Tactical Oversight Updates Tactical Map and passes on information to Host C2	Server/Switch	Recorder	
			Mission Operator Computers Status Display/Controls		
			Tactical Oversight Computer and tactical map Display/Controls	Mission Processor(3)	
			Wi-Fi Radio	Acoustic Comm	Acoustic/Wi-Fi
Classify FC.2	Process sensor input FC.2.1			Optical Sensor (4)	GPS/Acoustic Navigation Beacon
				Magnetic Sensor System	
				Recording System	
				Sonar Sensor System	
				Mission Processor(3)	
				INS/GPS(3)	
				DVL	
				Temperature Sensor(3)	
				Acoustic Comm	
	Determine if contact is mine-like or non-mine-like FC.2.2			Mission Processor(3)	
				Optical Sensor (4)	

Top Level Function	1st Level Sub function	Performing System				
		Human/Host Platform		MCM Vehicle	OTH Communication	
		Human	Sub Component	Sub Component	Sub Component	
				Magnetic Sensor System		
				Sonar Sensor System		
	Create message about contact classification FC.2.3	Mission Operator or Tactical Oversight query vehicle status - Tactical Oversight Updates Tactical Map and passes on information to Host C2	Server/Switch	Recorder	Acoustic/Wi-Fi	
			Mission Operator Computers Status Display/Controls	Mission Processor(3)		
			Tactical Oversight Computer and tactical map Display/Controls			
			Wi-Fi Radio	Acoustic Comm		
Identify FI.3	Determine if mine-like contact is a bottom mine FI.3.1			Mission Processor(3)		
				Optical Sensor (4)		
				Magnetic Sensor System		
				Sonar Sensor System		
	Determine if mine-like contact is a moored mine FI.3.2			Mission Processor(3)		
				Optical Sensor (4)		
				Magnetic Sensor System		
				Sonar Sensor System		
				Mission Processor(3)		

Top Level Function	1st Level Sub function	Performing System				
		Human/Host Platform		MCM Vehicle	OTH Communication	
		Human	Sub Component	Sub Component	Sub Component	
	Determine if mine-like contact is a drifting mine FI.3.3			Optical Sensor (4)		
				Magnetic Sensor System		
				Sonar Sensor System		
	Determine if mine-like contact should be avoided FI.3.4	Tactical Oversight query vehicle status - Tactical Oversight Updates Tactical Map and makes determination if contact should be avoided - passes information to Host C2	Server/Switch	Mission Processor(3)	Acoustic/Wi-Fi	
			Mission Operator Computers Status Display/Controls	Optical Sensor (4)		
			Tactical Oversight Computer and tactical map Display/Controls	Magnetic Sensor System		
			Wi-Fi Radio	Sonar Sensor System		
				Acoustic Comm		
	Create message about mine identification FI.3.5	Mission Operator or Tactical Oversight query vehicle status - Tactical Oversight Updates Tactical Map and passes on information to Host C2	Server/Switch	Mission Processor(3)	Acoustic/Wi-Fi	
			Mission Operator Computers Status Display/Controls	Recorder		
			Tactical Oversight Computer and tactical map Display/Controls	Acoustic Comm		
			Wi-Fi Radio			

Top Level Function	1st Level Sub function	Performing System			
		Human/Host Platform		MCM Vehicle	OTH Communication
		Human	Sub Component	Sub Component	Sub Component
Engage FE.4.0	Create neutralization plan FE.4.1	Tactical Oversight. Creates Neutralization Plan and passes it onto Host C2 and Programs Vehicle	Server/Switch	Mission Processor(3)	Acoustic/Wi-Fi
			Mission Operator Computers Status Display/Controls		
			Tactical Oversight Computer and tactical map Display/Controls		
			Wi-Fi Radio		
	Reacquire FE.4.2	Mission Operator or Tactical Oversight query vehicle status - Tactical Oversight Monitors	Server/Switch	Magnetic Sensor System	GPS/Acoustic Navigation Beacon
				Sonar Sensor System	
				Mission Processor	
				Power System	
			Mission Operator Computers Status Display/Control	Optical Sensor	
				Magnetic Sensor System	
			Mission Operator Computers Status Display/Controls	Recording System	
				Propulsion System	Acoustic/Wi-Fi
			Wi-Fi Radio	Sonar Sensor System	
				Mission Processor(3)	
				Acoustic Comm	
	Neutralize contact FE.4.3	Tactical Oversight Monitors	Mission Operator Computers Status Display/Control	Mission Processor	GPS/Acoustic Navigation Beacon
				INS/GPS	
				DVL	
				Pressure Depth Sensor	
			Server	Optical Sensors	
			Wi-Fi Radio	Acoustic Comm	Acoustic/Wi-Fi
		Tactical Oversight Commands Neutralization	Tactical Oversight Computer and tactical map Display, and Control	Neutralizer	

Top Level Function	1st Level Sub function	Performing System			
		Human/Host Platform		MCM Vehicle	OTH Communication
		Human	Sub Component	Sub Component	Sub Component
	Create message about engagement results FE.4.4	Tactical Oversight commands	Server	Mission Processor(3)	
			Tactical Oversight Computer and tactical map Display, and Control	Acoustic Comm	Acoustic/Wi-Fi
			Wi-Fi Radio		
Communicate FCO.6	Receive communications FCO.6.1		Wi-Fi Radio	Acoustic Comm	Acoustic/Wi-Fi
			Server	Mission Processor(3)	
			Switch		
	Transmit communications FCO.6.2	Sends Tasking	Wi-Fi Radio	Acoustic Comm	Acoustic/Wi-Fi
			Server	Mission Processor(3)	
			Switch		
	Determine status FCO.6.3	Tactical Oversight and Pilots monitor Vehicle Status	Wi-Fi Radio	Acoustic Comm	Acoustic/Wi-Fi
			Server	Mission Processor(3)	
			Pilot & Co-Pilot Computers Vehicle Status/Navigation Display		
			Recorder		
			Tactical Oversight Computer and tactical map Display		
	Store information FCO.6.4		Recorder/ Playback	Recording System	
			Server	Mission Processor(3)	

2. Alternative One Components mapped to Requirements

Table 51 depicts the Alternative One components mapped to the high level system requirements.

Table 51. Alternative One System Components Mapped to Requirements

Table lists System Requirements allocated to system components.

	MCM Advanced System											
	UUV System						OTH Comm. System	Host Platform MCM System				Local Operator
System Requirements vs. System Components	UUV Navigation System	UUV Mission Processing System	UUV Communication System	UUV Propulsion System	UUV Power System	UUV Neutralizer	Communication Link	Host Platform Launch & Recovery	Host Platform MCM Communication System	Host Platform MCM C2 & Processing System	Host Platform Fuel/Power Distribution System	Local Operator MCM System
REQ 1.0: Clandestine Operations	X		UA	X	X	X	BW	M	X			
REQ 2.0: Precise Navigation	3	3	A	X								
REQ 3.0: Autonomous Operational Modes	F	F	F	F	F	T	F		X	X		
REQ 4.0: Processing Capabilities	3	3	3									
REQ 5.0: MCM Communication		3	UA				BW		W	X		
REQ 6.0: Endurance	3	3	UA	X	X							
REQ 7.0: Operational Environment	X	X	X	X	X	X						
REQ 8.0: Deployment Distance	3	3	A	X	X	X	BW	M	A		X	
REQ 9.0: Detect and Classify Mines	3	3										

Note: The letter "X" indicates the component affects solving the requirement regardless of alternative. "UA" indicates under water acoustic communication. "M" indicates Multiple Platforms can deploy system. "BW" indicates Buoy Acoustic/Wi-Fi network. "A" indicates acoustic aided. "3" indicates there are three independent systems performing requirement. "F" indicates that it is fully autonomous operation. "T" indicates that it is Tele-operated. "W" indicates Wi-Fi Radio.

B. ALTERNATIVE TWO MAPPING

1. Alternative Two Components Mapped to Functions

Table 52 summarizes the how each component addresses the functions explored in this report (search, detect, identify, engage, and communicate). Table 52 also shows the breakout of tasking that is performed by human operators, the MCM ship, and the SPUDS for Alternative Two.

Table 52. Alternative Two Functions Allocated to System Components

This table depicts functions allocated to the Advanced MCM system for Alternative Two.

Top Level Function	1st Level Sub function	Performing System		
		Human/Host Platform		MCM Vehicle
		Human	Sub Component	Sub Component
Search FS.7	Enter operational area FS.7.1	Pilot, Co-Pilot and Tactical Oversight Monitors vehicle status. Pilot directs/commands vehicle	Computer System	Propulsion System
			Pilot & Co-Pilot Computers Vehicle Status/Navigation Display	MSN Processor
			Steering Control(s)	INS/GPS
			Server	DVL
			Recorder	Depth/Pressure Sensor
			TCDL	TCDL
	Activate search sensors FS.7.2	Pilot, Co-Pilot and Tactical Oversight Monitors vehicle status. Co-Pilot directs vehicle to turn on sensors	TCDL	Optical Sensor (2) Optical Sensors
			Control Panel	Magnetic Sensor System Deploy Magnetic Gradiometer
			Pilot, Co-Pilot, & Tactical Oversight Computers and vehicle Status Displays	Sonar Sensor System (1)
				Power System
	Follow search commands FS.7.3	Pilot, Co-Pilot and Tactical Oversight Monitors vehicle status. Pilot directs/commands vehicle to follow search patterns	TCDL	TCDL
			Control Panel	INS/GPS
			Pilot & Co-Pilot Computers Vehicle Status/Navigation Display	DVL
			Pilot & Co-Pilot Controls	Propulsion System
				Mission Processor
				Power System
	Record platform location FS.7.4	Pilot, Co-Pilot and Tactical Oversight Monitors vehicle position	TCDL	TCDL
			Server	INS/GPS
			Recorder	
			Pilot & Co-Pilot Vehicle Computers Status Display	Mission Processor
			Tactical Oversight Computer and tactical map Display	Pressure Depth Sensor
	Create mission complete message	Pilot, Co-Pilot and Tactical Oversight	TCDL	TCDL

Top Level Function	1st Level Sub function	Performing System: Human/Host Platform – Human	Performing System: Human/Host Platform – Sub Component	Performing System: MCM Vehicle – Sub Component
	FS.7.5	Monitors vehicle Monitors Vehicle Status on mission	Server	
			Recorder	
			Pilot & Co-Pilot Vehicle Computers Status Display	Mission Processor
			Tactical Oversight Computer and tactical map Display	
	Deactivate search sensors FS.7.6	Pilot, Co-Pilot and Tactical Oversight Monitors vehicle status. Co-Pilot directs vehicle to turn OFF sensors	Server	Optical Sensor
			Recorder	Magnetic Sensor System
			Pilot & Co-Pilot Vehicle Computers Status Display	Sonar Sensor System
			Tactical Oversight Computer and tactical map Display	Mission Processor
			TCDL	Power System
				TCDL
Detect FD.1	Receive information from sensors indicating contact in the area FD.1.1	3 Mission Analysis analyze data and determine contact and passes info to - Tactical Oversight	MA Computer System, and Sensor Displays,	Optical Sensor
			Tactical Oversight Computer and tactical map Display,	Magnetic Sensor System
			Recording System	Recording System
			Server	Sonar Sensor System
				Mission Processor
			TCDL	TCDL
	Record location of contact FD.1.2	Tactical Oversight - plots contact on tactical map and passes information onto Host C2	Tactical Oversight Computer and tactical map Display,	
			Server	
			Recorder	
	Record environmental information from sensors FD.1.3	3 Mission monitor Environmental data Co-Pilot monitors depth	MA Computer System, and Sensor Displays,	Pressure Sensor
				Temperature Sensor
			Co-Pilot Computer and vehicle status Display,	Mission Processor
			Recording System	
			Server	TCDL
			TCDL	
	Create message about detection in the area and its location FD.1.4	3 Mission Analysis analyze data and determine contact and passes info to - Tactical Oversight. Tactical oversight passes information on Host Platform C2	Server	
			MA Computer System, Sensor Displays, and controls	
			Tactical Oversight Computer and tactical map Display, and controls	

Top Level Function	1st Level Sub function	Performing System		
		Human/Host Platform		MCM Vehicle
		Human	Sub Component	Sub Component
Classify FC.2	Process sensor input FC.2.1	3 Mission Analysis analyze data	Server	
			MA Computer System, Sensor Displays, and controls	
			Recording System	
	Determine if contact is mine-like or non-mine-like FC.2.2	3 Mission Analysis analyze data Decision to determine Mine Contact. Tactical Oversight Monitors	Server	
			MA Computer System, Sensor Displays, and controls	
			Recording System	
			Tactical Oversight Computer and tactical map Display,	
	Create message about contact classification FC.2.3	3 Mission Analysis analyze data and determine contact and passes info to - Tactical Oversight. Tactical oversight updates Tactical Map and passes information on to Host C2	Server	
			MA Computer System, Sensor Displays, and controls	
			Recording System	
			Tactical Oversight Computer and tactical map Display,	
Identify FI.3	Determine if mine-like contact is a bottom mine FI.3.1	3 Mission Analysis analyze data to to determine Mine Contact is bottom mine. Tactical Oversight Monitors	Server	
			MA Computer System, Sensor Displays, and controls	
			Recording System	
			Tactical Oversight Computer and tactical map Display,	
	Determine if mine-like contact is a moored mine FI.3.2	3 Mission Analysis analyze data to determine Mine Contact is moored mine. Tactical Oversight Monitors	Server	
			MA Computer System, Sensor Displays, and controls	
			Recording System	
			Tactical Oversight Computer and tactical map Display,	
	Determine if mine-like contact	3 Mission Analysis analyze data to	Server	

Top Level Function	1st Level Sub function	Performing System		
		Human/Host Platform		MCM Vehicle
		Human	Sub Component	Sub Component
	is a drifting mine FI.3.3	determine Mine Contact is a drifting mine. Tactical Oversight Monitors	MA Computer System, Sensor Displays, and controls	
			Recording System	
			Tactical Oversight Computer and tactical map Display,	
	Determine if mine-like contact should be avoided FI.3.4	3 Mission Analysis analyze data to determine Mine like Contact should be avoided. Tactical Oversight Monitors	Server	
			MA Computer System, Sensor Displays, and controls	
			Recording System	
			Tactical Oversight Computer and tactical map Display,	
	Create message about mine identification FI.3.5	3 Mission Analysis analyze data identify Mine like Contact and pass it to Tactical Oversight. Tactical Oversight Updates Tactical Map and passes information to Host C2	Server	
			MA Computer System, Sensor Displays, and controls	
			Recording System	
			Tactical Oversight Computer and tactical map Display,	
Engage FE.4	Create neutralization plan FE.4.1	Tactical Oversight. Creates Neutralization Plan and passes it onto Host C2 and Pilots	Tactical Oversight Computer and tactical map Display,	
		Pilots Set Waypoints in vehicle	Pilot & Co-Pilot Computers Vehicle Status/Navigation Display	Mission Processor
			Server	
			TCDL	TCDL
	Reacquire FE.4.2	Command	TCDL	TCDL
		Tactical Oversight Monitors	Tactical Oversight Computer and tactical map Display,	INS/GPS
		Pilot & Copilot Navigate Vehicle to Mines Last Known Location	Pilot & Co-Pilot Computers Vehicle Status/Navigation Display	DVL
				Propulsion System
				Mission Processor
		MA monitor Sensor Displays for Contact	MA Computer System, Sensor Displays, and controls	Power System
				Optical Sensor (2) Optical Sensors

Top Level Function	1st Level Sub function	Performing System		
		Human/Host Platform		MCM Vehicle
		Human	Sub Component	Sub Component
			Server	Magnetic Sensor System Deploy Magnetic Gradiometer
				Sonar Sensor System (1)
	Neutralize contact FE.4.3	Pilot, Co-Pilot guide vehicle to mine monitor status. Tactical Oversight Monitors	Pilot & Co-Pilot Computers Vehicle Status/Navigation Display	Mission Processor
				INS/GPS
				DVL
				Pressure Depth Sensor
			Server	Optical Sensors
			TCDL	TCDL
		Tactical Oversight Commands Neutralization	Tactical Oversight Computer and tactical map Display, and Control	Neutralizer
	Create message about engagement results FE.4.4	Tactical Oversight commands	Server	Mission Processor
			TCDL	TCDL
Communicate FCO.6	Receive communications FCO.6.1		TCDL	TCDL
			Server	Mission Processor
			Switch	
	Transmit communications FCO.6.2	Sends Tasking	TCDL	TCDL
			Server	Mission Processor
			Switch	
	Determine status FCO.6.3	Tactical Oversight and Pilots monitor Vehicle Status	TCDL	TCDL
			Server	Mission Processor
			Pilot & Co-Pilot Computers Vehicle Status/Navigation Display	
			Recorder	
			Tactical Oversight Computer and tactical map Display	
	Store information FCO.6.4		TCDL	Recording System
			Server	Mission Processor

2. Alternative Two Components Mapped to Requirements

Table 53 depicts the Alternative Two components mapped to the high level system requirements.

Table 53. Alternative Two System Components Mapped to Requirements

Table lists System Requirements allocated to system components.

	MCM Advanced System											
	UUV System						OTH Comm. System	Host Platform MCM System				Local Operator
System Requirements vs. System Components	UUV Navigation System	UUV Mission Processing System	UUV Communication System	UUV Propulsion System	UUV Power System	UUV Neutralizer	Communication Link	Host Platform Launch & Recovery	Host Platform MCM Communication System	Host Platform MCM C2 & Processing System	Host Platform Fuel/Power Distribution System	Local Operator MCM System
REQ 1.0: Clandestine Operations	X		RDT	X	X	X	RDA	M	RD	1		
REQ 2.0: Precise Navigation	1	1	RDT	X			RDA		RD	1		
REQ 3.0: Autonomous Operational Modes	1	T	RDT	T	T	T	RDA		RD	1		
REQ 4.0: Processing Capabilities	1	1	1				RDA		RD	6		
REQ 5.0: MCM Communication		1	RT				RDA		RD	1		
REQ 6.0: Endurance	1	1	RDT	X	X		RDA		RD	1		
REQ 7.0: Operational Environment	X	X	X	X	X	X						
REQ 8.0: Deployment Distance	1	1	RDT	X	X	X	RDA	M	RD	1	X	
REQ 9.0: Detect and Classify Mines		1	RDT				RDA		RD	4		

Note: "X" indicates the component affects solving the requirement regardless of alternative. "RDT" indicates "Radio Data link, Tether Antenna" communication. "RDA" indicates "Radio Data link - Airborne Platform". "M" indicates "Multiple Platforms" can deploy system. "T" indicates "Tele-operation" mode of operation. "1" indicates there is one independent system performing requirement. "4" indicates there are four independent systems performing requirement. "6" indicates there are six independent systems performing requirement.

C. ALTERNATIVE THREE MAPPING

1. Alternative Three Components Mapped to Functions

Table 54 summarizes the how each component addresses the functions explored in this report (search, detect, identify, engage, and communicate). Table 54 also shows the breakout of tasking that is performed by human operators, the MCM ship, and the SPUDS for Alternative Three.

Table 54. Alternative Three Functions Allocated to System Components

This table depicts functions allocated to the Advanced MCM system for Alternative Two.

<table>
<tr><th rowspan="3">Top Level Function</th><th rowspan="3">1st Level Sub function</th><th colspan="6">Performing System</th></tr>
<tr><th>Human/
Host Platform</th><th></th><th>MCM Vehicle</th><th colspan="2">Local Operator</th></tr>
<tr><th>Human</th><th>Sub Component</th><th>Sub Component</th><th>Human</th><th>Component</th></tr>
<tr><td rowspan="10">Search 7</td><td rowspan="5">Enter operational area
FS.7.1</td><td rowspan="5">Communication Operator Monitors and acknowledges status</td><td rowspan="5">Ship Communication System</td><td>Propulsion System</td><td>Local launches vehicle from boat</td><td></td></tr>
<tr><td rowspan="2">Communication. System</td><td rowspan="3">Local MCM Vehicle Operator Loads Current Position into MCM Vehicle</td><td>VHF/UHF Radio</td></tr>
<tr><td>GPS Radio</td></tr>
<tr><td rowspan="2">Power Distribution System</td><td>Control Panel/Display</td></tr>
<tr><td>MCM Team Leader communicates status back to Host Platform that there in the AO.</td><td>SINCGARS/JTRS</td></tr>
<tr><td rowspan="5">Activate search sensors
FS.7.2</td><td rowspan="5"></td><td rowspan="5"></td><td>Optical Sensor</td><td rowspan="5">Local MCM Vehicle Operator Commands Vehicle to turn on sensors</td><td rowspan="2">Control Panel/Display</td></tr>
<tr><td>Magnetic Sensor Sys</td></tr>
<tr><td>Sonar Sensor Sys</td><td rowspan="3">VHF/UHF Radio</td></tr>
<tr><td>Pwr Sys</td></tr>
<tr><td>Interface Box</td></tr>
</table>

Top Level Function	1st Level Sub function	Performing System				
		Human/ Host Platform		MCM Vehicle	Local Operator	
		Human	Sub Component	Sub Component	Human	Component
	Follow search commands FS.7.3	Communication Operator Monitors and acknowledges status	Ship Communication System	Rate gyro	Local MCM Vehicle Operator drives vehicle along program path while monitoring vehicle status.	Control Panel/Display
				Compass		VHF/UHF Radio
				Propulsion System		LO Vehicle Ranging Equipment
				Power Distribution System	MCM Team Leader informs Host Platform of Status	
				DVL		
	Record platform location FS.7.4			UUV Recorder		
				UUV Interface Box		
				UUV Rate Gyro & Compass		
				UUV DVL		
				UUV Depth Presser/Temp Sensor		
	Create mission complete message FS.7.5	Communication Operator Monitors and acknowledges status	Ship Communication System		MCM Team Leader informs Host Platform of Status	Radio Comms, SINCGARS/JTRS
	Deactivate search sensors FS.7.6			Optical Sensor	Local MCM Vehicle Operator Commands Vehicle to turn off sensors	VHF/UHF Radio
				Magnetic Sensor Sys		Control Panel/Display
				Sonar Sensor Sys		

Top Level Function	1st Level Sub function	Performing System				
		Human/ Host Platform		MCM Vehicle	Local Operator	
		Human	Sub Component	Sub Component	Human	Component
				Power Distribution System	MCM Team Leader communicates status back to Host Platform that there in the AO.	SINCGARS/JTRS
Detect FD.1	Receive information from sensors indicating contact in the area FD.1.1	4 MA Analyze Data Tactical Oversight Monitors	HP MCM Recorder Play Back	Optical Sensor	Local MCM Operators Retrieve recorded data from vehicle and transport it back to the MCM host Plat form	
			HP Video Encoder	Magnetic Sensor Sys		
			HP MCM Server	Recording System		
			HP MCM Switch			
			MA Computer/Display	Sonar Sensor Sys		
			Tactical Oversight Computer/Display			
	Record location of contact FD.1.2	4 MA Analyze Data and determine contacts with locations Tactical Oversight Monitors	HP MCM Recorder Play Back			
			HP Video Encoder			
			HP MCM Server			
			HP MCM Switch			
			MA Computer/Display			
			Tactical Oversight Computer/Display			
	Record environmental information from	4 MA Analyze Data and monitor and corrects	HP MCM Recorder Play Back	Pressure Sensor		

Top Level Function	1st Level Sub function	Performing System				
		Human/ Host Platform		MCM Vehicle	Local Operator	
		Human	Sub Component	Sub Component	Human	Component
	sensors FD.1.3	Tactical Oversight Monitors	HP MCM Server	DVL		
			HP MCM Switch	Temperature Sensor		
			MA Computer/Display	Recorder		
			Tactical Oversight Computer/Display	Interface Box		
				Rate Gyro/Compass		
	Create message about a detection in the area and its location FD.1.4	4 Mission Analysis analyze data and determine contact and passes info to - Tactical Oversight. Tactical oversight passes information on Host Platform C2 and updates tactical map	HP MCM Play Back Recorder			
			HP MCM Server			
			HP MCM Switch			
			MA Computer/Display			
			Tactical Oversight Computer/Display			
Classify FC.2	Process sensor input FC.2.1	4 Mission Analysis analyze data and determine contact Tactical Oversight. Monitors	HP MCM Recorder Play Back			
			HP MCM Server			
			HP MCM Switch			

Top Level Function	1st Level Sub function	Performing System				
		Human/ Host Platform		MCM Vehicle	Local Operator	
		Human	Sub Component	Sub Component	Human	Component
			MA Computer/Display			
			Tactical Oversight Computer/Display			
	Determine if contact is mine-like or non-mine-like FC.2.2	4 Mission Analysis analyze data and determine if contact is Mine-Like of Non Mine- like, Tactical Oversight. Monitors	HP MCM Play Back Recorder			
			HP MCM Server			
			HP MCM Switch			
			MA Computer/Display			
			Tactical Oversight Computer/Display			
			HP MCM Play Back Recorder			
	Create message about contact classification FC.2.3	4 Mission Analysis Operators analyze data and determine contact classification and passes info to - Tactical Oversight. Tactical oversight passes information on Host Platform C2 and updates tactical map	HP MCM Play Back Recorder			
			HP MCM Server			
			HP MCM Switch			
			MA Computer/Display			
			Tactical Oversight Computer/Display			
Identify FI.3	Determine if mine-like contact is a bottom mine FI.3.1	4 Mission Analysis Operators analyze data and determined if mine-like contact is a bottom mine- Tactical Oversight. monitors	HP MCM Play Back Recorder			
			HP MCM Server			
			HP MCM Switch			
			MA Computer/Display			

Top Level Function	1st Level Sub function	Performing System				
		Human/ Host Platform		MCM Vehicle	Local Operator	
		Human	Sub Component	Sub Component	Human	Component
			Tactical Oversight Computer/Display			
	Determine if mine-like contact is a moored mine FI.3.2	4 Mission Analysis Operators analyze data and determined if mine-like contact is a moored mine-Tactical Oversight. monitor	HP MCM Play Back Recorder HP MCM Server HP MCM Switch MA Computer/Display Tactical Oversight Computer/Display			
	Determine if mine-like contact is a drifting mine FI.3.3	4 Mission Analysis Operators analyze data and determined if mine-like contact is a Drifting mine-Tactical Oversight. monitor	HP MCM Play Back Recorder HP MCM Server HP MCM Switch MA Computer/Display Tactical Oversight Computer/Display			
	Determine if mine-like contact should be avoided FI.3.4	Tactical Oversight determines routes and if mines should be avoided	HP MCM Server Tactical Oversight Computer/Display			
	Create message about mine identification FI.3.5	4 Mission Analysis analyze data identify Mine like Contact and pass it to Tactical Oversight. Tactical Oversight Updates Tactical Map and passes information to Host C2	HP MCM Play Back Recorder HP MCM Server HP MCM Switch MA Computer/Display Tactical Oversight Computer/Display			

Top Level Function	1st Level Sub function	Performing System				
		Human/ Host Platform		MCM Vehicle	Local Operator	
		Human	Sub Component	Sub Component	Human	Component
Engage FE.4	Create neutralization plan FE.4.1	Tactical Oversight. Creates Neutralization Plan and passes it onto Communication Operator	Tactical Oversight Computer and tactical map Display,		MCM Team Leader receives mission from Host Platform of Status	Radio Comms, SINCGARS/JTRS
		Communication Operator instructs Local operator team on mission				
	Reacquire FE.4.2			Propulsion System	MCM Team Leader Instructs MCM Vehicle Operator to load coordinates of mine into vehicle.	Control Panel/Display
				Communication. System		
				Power Distribution System		VHF/UHF Radio
				Optical Sensor		
				Magnetic Sensor Sys	Local MCM Vehicle Operator Loads Current Position and Mine Position into MCM Vehicle	
				Sonar Sensor Sys		LO Vehicle Ranging Equipment
				Pwr Sys		
				Interface Box		
	Neutralize contact FE.4.3			Propulsion System	Local MCM Vehicle guide vehicle to mine and monitors status.	Control Panel/Display
				Communication. System		
				Power Distribution System		VHF/UHF Radio
				Optical Sensor	MCM Team Leader Commands Neutralization	
				Magnetic Sensor Sys		
				Sonar Sensor Sys		LO Vehicle Ranging

Top Level Function	1st Level Sub function	Performing System				
		Human/ Host Platform		MCM Vehicle	Local Operator	
		Human	Sub Component	Sub Component	Human	Component
				Pwr Sys DVL Depth Pressure/Temp Sensor Interface Box		Equipment
	Create message about engagement results FE.4.4	Communication Operator receives Local operator message and passes it to Tactical Oversight	HP MCM Server HP MCM Switch		MCM Team Leader Informs Host Platform of Mine Neutralization	Radio Comms, SINCGARS/JTRS
		Tactical Oversight updates Tactical Map and passes status to host platform C2	Tactical Oversight Computer/Display			
Communicate	Receive communications FCO.6.1	Receives Status	SINCGARS/JTRS		Sends Status	Radio Comms, SINCGARS/JTRS
	Transmit communications FCO.6.2	Sends Tasking	SINCGARS/JTRS		Receives Tasking	
	Determine status FCO.6.3			Comm System	Determines Status	Remote Control Panel
	Store Information FCO.6.4	Record	SINCGARS/JTRS	Recording System		

2. Alternative Three Components Mapped Requirements

Table 55 depicts the Alternative Three components mapped to high level system requirements.

Table 55. Alternative Three System Components Mapped to Requirements

Table lists System Requirements allocated to system components.

	MCM Advanced System											
	UUV System						**OTH Comm. System**	**Host Platform MCM System**				**Local Operator**
System Requirements vs. System Components	UUV Navigation System	UUV Mission Processing System	UUV Communication System	UUV Propulsion System	UUV Power System	UUV Neutralizer	Communication Link	Host Platform Launch & Recovery	Host Platform MCM Communication System	Host Platform MCM C2 & Processing System	Host Platform Fuel/Power Distribution System	Local Operator MCM System
REQ 1.0: Clandestine Operations	X		RDT	X	X	X	RD	M	RD	1		1
REQ 2.0: Precise Navigation	1	I	RDT	X								1
REQ 3.0: Autonomous Operational Modes	1	R/T	RDT	T	T	T	RD		RD	1		1
REQ 4.0: Processing Capabilities	1	1	1						1	4 PMA		1
REQ 5.0: MCM Communication		1	RDT				RD		RD	1		1
REQ 6.0: Endurance	1	1	RDT	X	X							1
REQ 7.0: Operational Environment	X	X	X	X	X	X						1
REQ 8.0: Deployment Distance	1	1	RDT	X	X	X		M			X	1
REQ 9.0: Detect and Classify Mines		1								5 PMA		1

Note: "X" indicates the component affects solving the requirement regardless of alternative. "RDT" indicates "Radio Data link, Tether Antenna" communication. "RDA" indicates "Radio Data link - Airborne Platform". "M" indicates "Multiple Platforms" can deploy system. "R/T" indicates system is a hybrid of Remote Control/Tele-operated. "1" indicates there is one independent system performing requirement. "4 PMA" indicates there are four independent systems and personal performing post mission analysis. "5 PMA" indicates there are five independent systems and personal performing post mission analysis.

APPENDIX F: MODELING EFFORTS

A. INITIAL MODELING EFFORTS

A BOE model was created in Excel as an experiment to determine the starting point for the ExtendSIM model that would be used for simulation. The intention of the initial modeling was to test the methods used on the alternative architectures and to use information based on an existing system to develop a baseline for comparison. The MK18 UUV was used as the baseline system since performance information was available from the CRD and from results of testing performed by JHU (PMS 408, 2011; Pollitt, 2011). The initial parameters used for the MK18 UUV BOE model are found in Table 56.

Table 56. BOE Initial Parameters and Results

This is a list of the parameters used in the BOE model when using the MK-18 system.

Parameter	Value
Forward speed	1.5 meters/second or 1.64 yards/second
Probability of detection and classification (P_dP_c)	0.75
Probability of identification (P_i)	0.8
False Alarm Rate (FAR)	0.15
Distance between objects in BOE	280 meters
BOE minefield area	500 meters by 500 meters
Track width	4 meters
Number of tracks	125
Total distance traveled during BOE	63000 meters
Number of bottom mines	105
Number of moored mines	45
Number of non-mines	75
Time to complete one pass	42000 s or 11.66666667 hours
Percentage of mines not detected	38%
Average Coverage Rate (ACR)	0.006248 n.m.^{2}/hr

The main purpose of the BOE was to verify the initial ExtendSIM simulation results, and verify the methods were consistent. The creation of the BOE and ExtendSIM models were performed, before the architectures were defined, to ensure a quick transition into modeling the final alternatives. One assumption made for the MK-18 model includes that the vehicle does not stop or loiter over mines during the search. The model also assumed that the system will follow a grid pattern, but the turn radius for the vehicle is not being included.

Each track of the search pattern was decided to be four meters in the BOE. This pattern was influenced by a presentation by George Pollitt (Pollitt, 2011). The back of the envelope

model had the mines evenly distributed along the path, and the order of the mines and objects were randomly selected. The BOE also used an area of 500 by 500 meters as opposed to the 500 by 500 yards to simplify the initial math. The distribution of the mines and the size of the field were modified for the ExtendSIM model to be consistent with the DRM.

Minefield 1 was created using a uniform random distribution to determine the location of both the bottom and moored mines and non-mine objects, and can be seen in Figure 97. A uniform distribution was chosen with the assumptions that over time some mines may move based on currents and other factors. Also, the threat analysis showed that if the mines were delivered by aircraft, the minefield pattern would be random with a uniform distribution. In order to have the "most random" minefield, a uniform distribution was chosen. Since the DRM describes a sea floor with a slope of 1˚, the Excel file included a measurement in yards of the distance from the surface of the water to the sea floor. This distance was used to determine the distance from the mine hunting system to the bottom mines or non-mine objects. To further develop the model, moored mines should eventually include a measurement for length of tether to determine their exact three-dimensional position in the minefield.

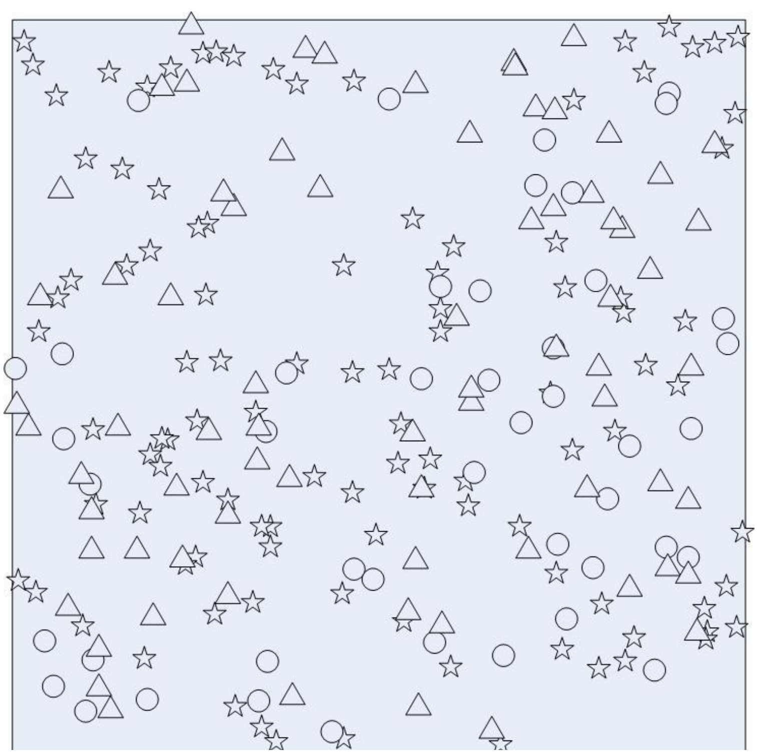

Figure 97. Minefield 1

The figure is a two-dimensional graphical representation of Minefield 1 used for the simulations. The locations of objects on the map are to scale; however, the sizes are not. The stars represent 105 bottom mines, the circles represent 45 moored mines and the triangles represent 75 non-mine objects.

Minefield 2 was produced as perimeter blocking minefield and with mines placed in lines to simulate an individual vehicle dropping mines during a short period of time. The arrangement of mines in Minefield 2 is shown in Figure 98. This minefield has 100 fewer mines than Minefield 1. The non-mine objects are the same as those used in Minefield 1 to simulate the same VSW area being cleared.

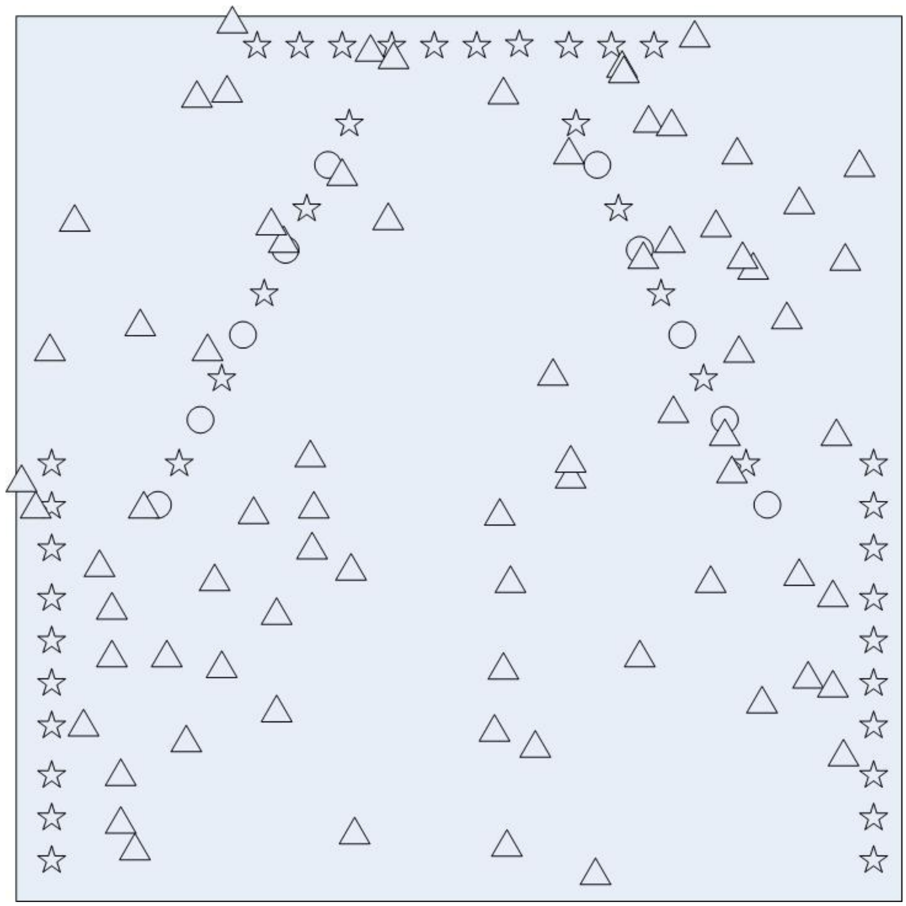

Figure 98. Minefield 2

The figure is a two-dimensional graphical representation of Minefield 2 used for the simulations. The locations of objects on the map are to scale; however, the sizes are not. The stars represent 40 bottom mines, the circles represent 10 moored mines and the triangles represent 75 non-mine objects.

The input databases for the first ExtendSIM model held the creation time, the minimum distance the system was from the mine, and the probability of detection for each of the mines and non-mine objects.

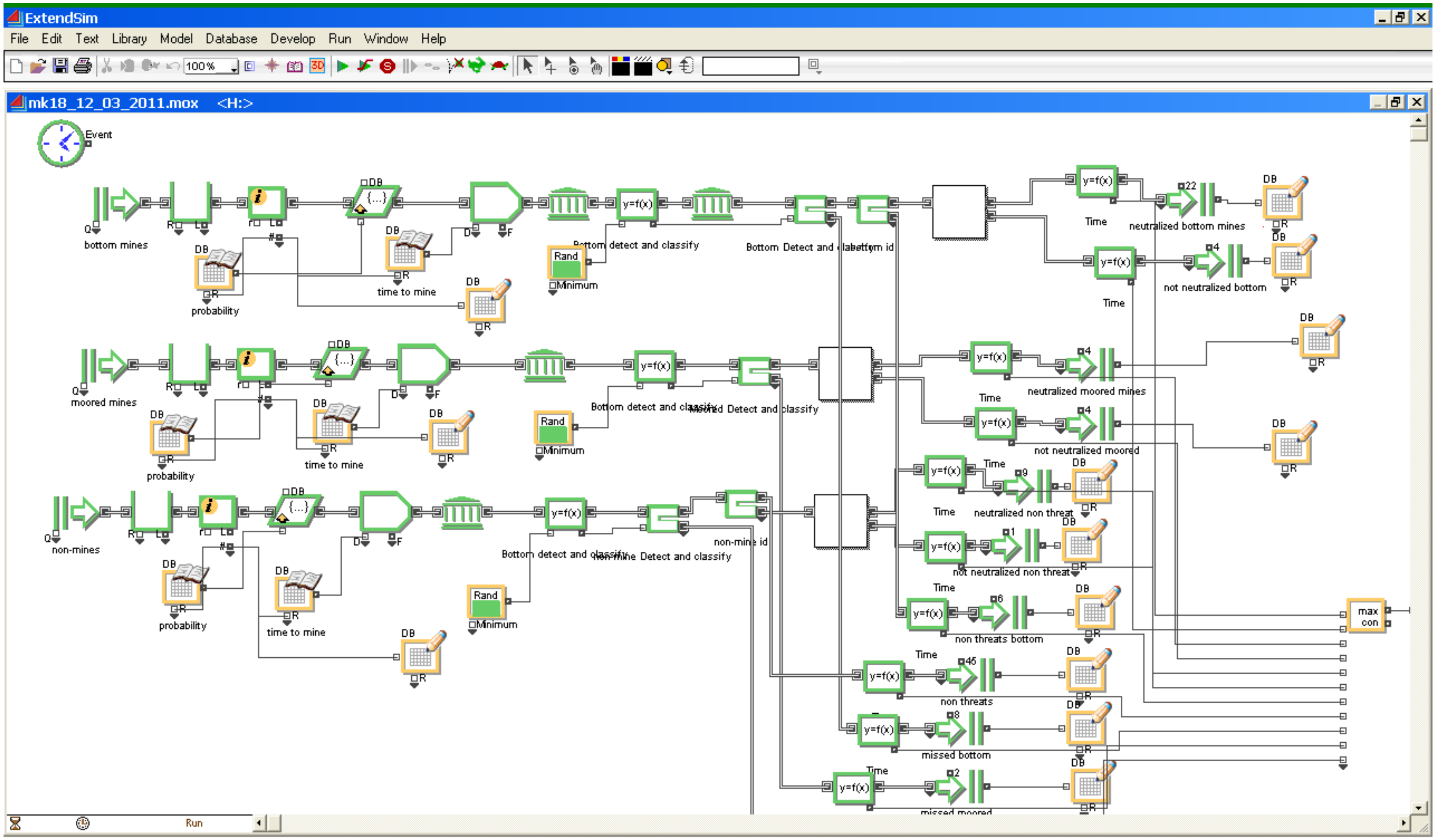

Figure 99. MK-18 ExtendSIM Model

The figure is a screen shot of the MK18 UUV version of the ExtendSIM model used for simulation.

A screen shot for the original MK-18 model can be seen in Figure 99. The model handled all the targets in a similar method. The target, whether a bottom mine, moored mine, or non-mine object, was created and assigned a delay. This delay represents the time the system would take to intercept the target. For the MK18 model it was assumed the system would perform the same "mow the grass" pattern as was modeled in the back of the envelope model. Based on a 1.5 meters/second rate, the times and distances were calculated in Excel and entered into the model's database. The target was then sent into an equation object which reads the probability of detection and classification (P_dP_c) from the database, and uses a uniform distributed random value to determine if the object was detected or not. The equation was used to control the value of the probability of detection for each target.

The model was intended to be able to handle various factors such as bottom mine burial, or target composition, factors which would directly affect the probability of detection of the sensors. For much of the original model testing a probability of 0.75 was used for P_dP_c. That model assumes that if a moored mine is detected, identification as a moored mine is certain. However, the non-mines and the bottom mines would have ground clutter to interfere with detection. A probability of 0.8 was included as the probability of correct identification (P_{id}) to allow the possibility that the sea-floor-located target may not be identified correctly. The values for P_dP_c and P_{id} were taken from the MK-18 CRD as threshold requirement values for future system performance (PMS 408, 2011).

If the target was identified as a mine, it was passed to a neutralization subroutine. The neutralization was produced assuming there were three chances to neutralize the mines. This would have allowed the model to handle the possibility of multiple attempts to neutralize the mine. The probability of neutralization (P_n) at each attempt was 0.5. This was selected since the MK18 UUV did not have any neutralization capability and was mainly done as a proof of concept for the model, and the values of P_n and the numbers of chances were selected by the group. In the neutralization object a delay was added assuming the MK18 UUV would finish the entire minefield before neutralization would occur. The delay was equal to the time the MK18 UUV was calculated to transit the entire minefield. This assumes the theoretical neutralization system moves at the same speed as the MK18 UUV, and follows the same path. After further research this portion of the model was removed when the neutralization function was removed from the bounded system.

The intention of modeling the MK18 UUV was not to create a highly accurate model of the MK18 UUV system, but as a test for the concepts of programming the model and to use as a baseline for comparison. Using the MK18 UUV model, 1000 iterations were performed.

For Minefield 1 the results showed on average, 43.73% of the mines remained in the area after one pass. The standard deviation of this percentage is 0.040. The average time to complete one pass of search and neutralization was 79833 seconds with a standard deviation of 364 seconds, or approximately 22 hours. The ACR was calculated at 0.002748 n.m.^{2}/hr.

For Minefield 2 the average results showed 45.11% of mines remaining in the area after one pass, with a standard deviation of 0.070. The average time to complete one pass of search and neutralization was 79260 seconds, with a standard deviation of 270 seconds. The ACR was calculated at 0.002768 n.m.^{2}/hr. Since the pattern of the search did not change between both minefields the completion times are similar.

The performance of the model was compared to the values determined for the MK18 UUV during testing performed by Johns Hopkins University (JHU) as 0.25 km^2/hr (Pollitt, 2011). Converting the JHU value into English units, the value is approximately 0.0726 n.m.^{2}/hr. Even though there were activities included in our definition of the ACR that were not considered in the JHU definition, the difference showed that the track width used in the model was too small and caused the ACR to be excessively low. When the track width was increased to 40 yards the ACR was calculated as 0.0506 n.m.^{2}/hr. This track width was used for the remainder of the modeling.

This initial work provided the framework for the follow-on modeling. The models were modified and showed where some of our assumptions needed to be updated. However the lessons learned in this initial modeling were useful to develop the final models used.

B. MODELING RESULTS

For each minefield, 1000 runs of the ExtendSIM model were performed on each architecture. Figure 100 displays that for Alternative One there is not a large difference in the ACR or the undetected mines metrics between Minefield 1 and Minefield 2. Since Alternative One has such a short time to detect and classify, this permits the ACRs to be similar. The histograms indicate that the data follows a normal distribution. Table 57 shows the values calculated based on the results of the simulations for Architecture One. This table shows the mean ACR for Minefield 1 was 0.0144 n.m.^{2}/hr with a standard deviation of 7.43E-05. For Minefield 2 the mean ACR was 0.014333 n.m.^{2}/hr with a standard deviation of 7.39E-05. The mean value for undetected mines in Minefield 1 was 0.1 with a standard deviation of 0.024. For Minefield 2 the mean value for undetected mines was 0.1 with a standard deviation of 0.043.

Table 57. Results from Architecture One

This table provides the values for the box plots for Architecture One and the standard deviation calculated based on 1000 runs of the model.

Minefield 1	ACR	Undetected Mines		Minefield 2	ACR	Undetected Mines
Min	0.014173	0.04		Min	0.01404	0
25th percentile	0.014369	0.086667		25th percentile	0.014283	0.06
Median	0.014419	0.1		Median	0.014334	0.1
75th percentile	0.014473	0.12		75th percentile	0.014386	0.12
Max	0.014639	0.186667		Max	0.014554	0.28
Mean	0.0144	0.1		Mean	0.014333	0.1
Standard deviation	7.43E-05	0.024		Standard deviation	7.39E-05	0.043

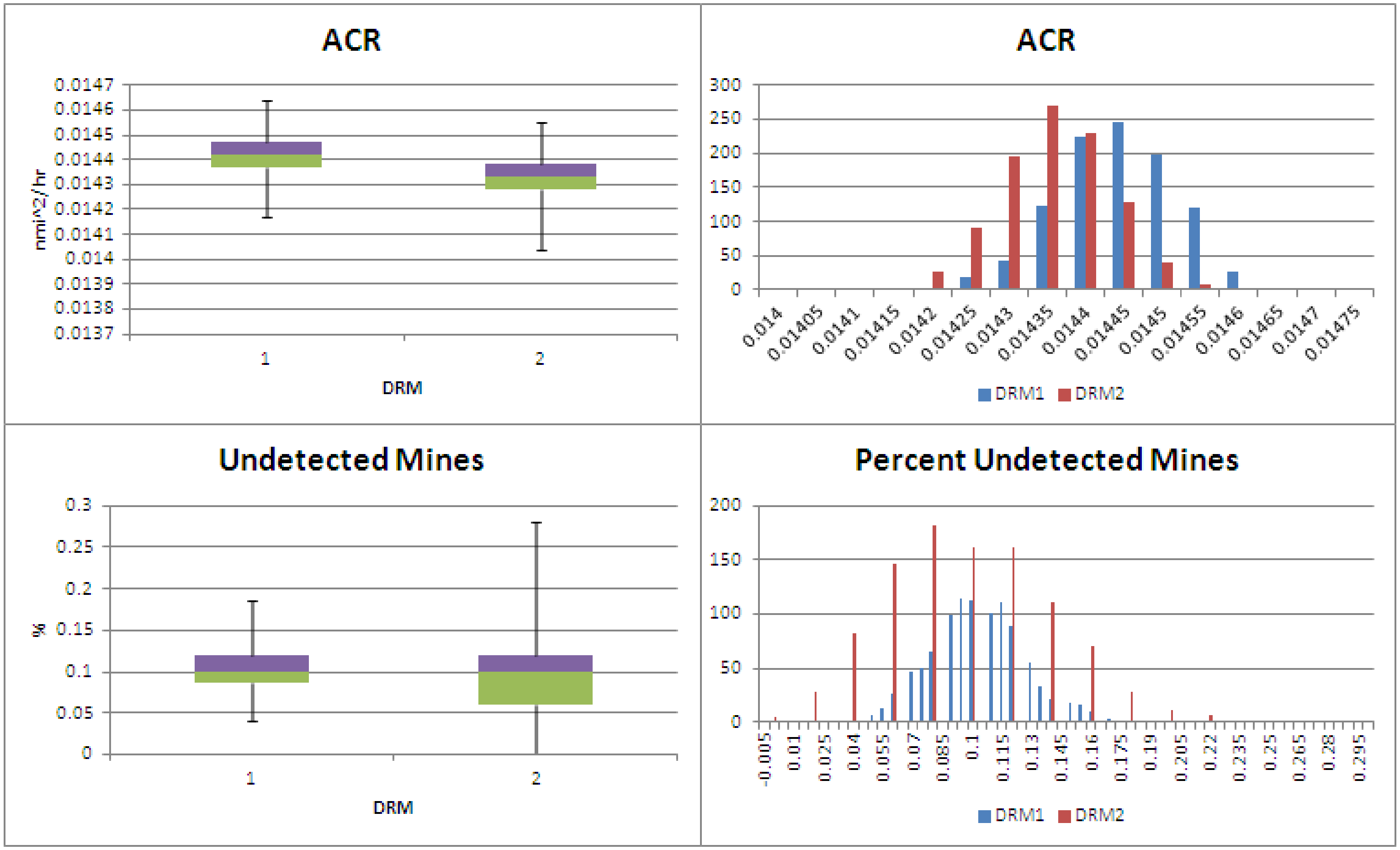

Figure 100. Modeling Results for Alternative One

This figure is a quad chart showing the results of the modeling for Architecture One. Displayed are the distributions of the metrics of ACR and for Undetected Mines, in both box chart form and histogram form. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25^{th} percentile to the 75^{th} percentile. Where the boxes change color shows the median value of the data.

Figure 101 shows that for Alternative Two the ACR for Minefield 2 is significantly higher than in Minefield 1. This is due to the wide differences in the time to detect and classify. Minefield 2 has far fewer mines to observe which would allow the vehicle a faster search time, resulting in a higher ACR. There is no significant difference in the number of mines left undetected between the minefields. Table 58 shows the values calculated based on the results of the simulations for Architecture Two.

Table 58. Results from Architecture Two

This table provides the values for the box plots for Architecture Two and the standard deviation calculated based on 1000 runs of the model.

Minefield 1	ACR	Undetected Mines		Minefield 2	ACR	Undetected Mines
Min	0.00289	0.113		Min	0.00502	0.04
25th percentile	0.00318	0.18		25th percentile	0.00564	0.16
Median	0.00326	0.2		Median	0.00580	0.2
75th percentile	0.00333	0.227		75th percentile	0.00599	0.24
Max	0.00358	0.313		Max	0.00677	0.38
Mean	0.00325	0.2		Mean	0.00581	0.2
Standard deviation	0.00011	0.0332		Standard deviation	0.00025	0.055

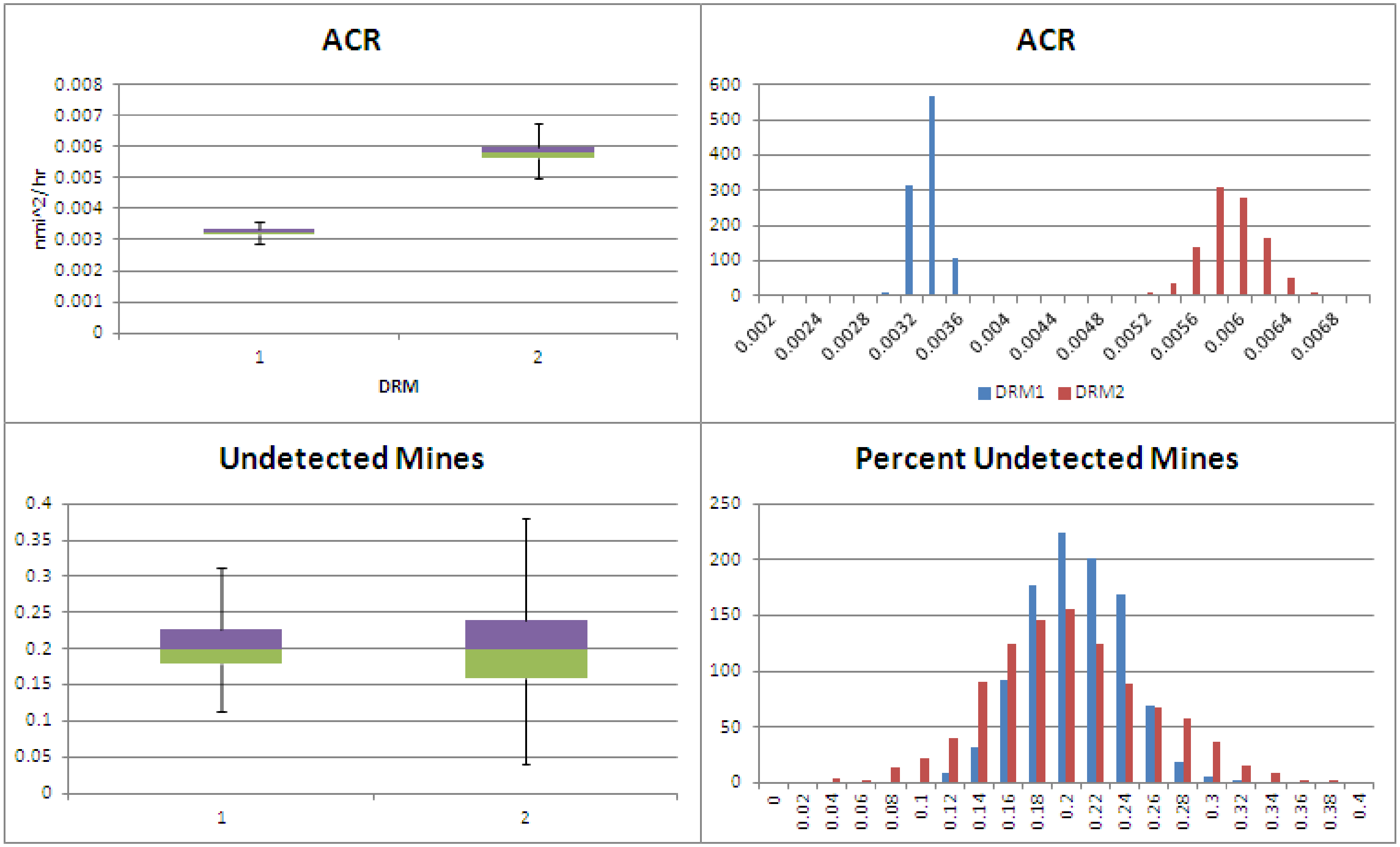

Figure 101. Modeling Results for Alternative Two

This figure is a quad chart showing the results of the modeling for Alternative Two. Displayed are the distributions of the metrics of ACR and for Undetected Mines, in both box chart form and histogram form. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

Figure 102 shows similar results to Figure 101 for Alternative Three in that the ACR is controlled by the amount of time it takes to detect and classify the mines. Table 59 shows the values calculated based on the results of the simulations for Architecture Three.

Table 59. Results from Architecture Three

This table provides the values for the box plots for Architecture Three and the standard deviation calculated based on 1000 runs of the model.

Minefield 1	ACR	Undetected Mines		Minefield 2	ACR	Undetected Mines
Min	0.00246	0.133		Min	0.00372	0.06
25th percentile	0.00262	0.193		25th percentile	0.00413	0.195
Median	0.00267	0.213		Median	0.00422	0.24
75th percentile	0.00273	0.24		75th percentile	0.00431	0.26
Max	0.00291	0.327		max	0.00466	0.44
Mean	0.00267	0.215		Mean	0.00422	0.231
Standard deviation	7.53E-05	0.0321		Standard deviation	0.000133	0.0559

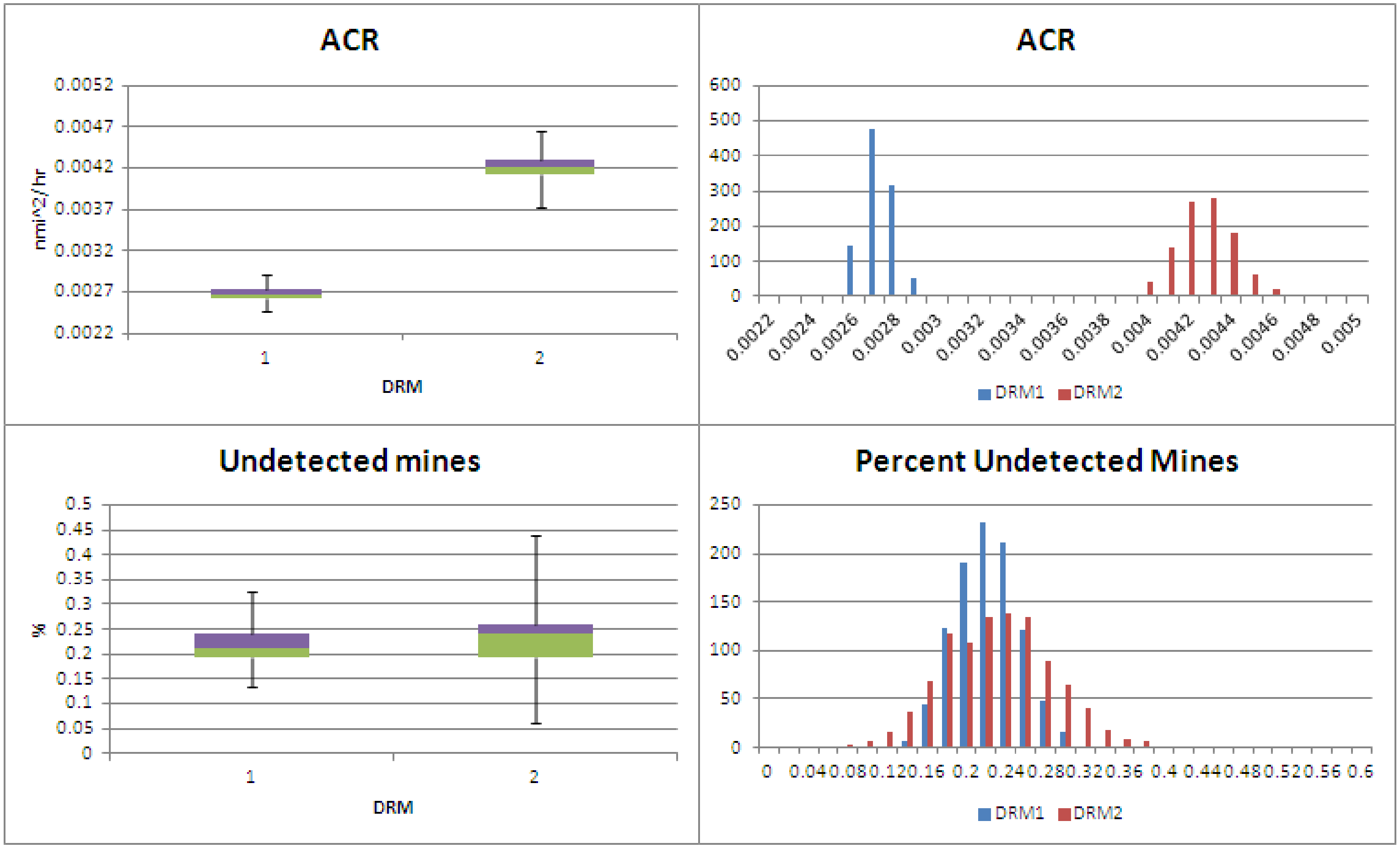

Figure 102. Modeling Results for Alternative Three

This figure is a quad chart showing the results of the modeling for Alternative Three. Displayed are the distributions of the metrics of ACR and for Undetected Mines, in both box chart form and histogram form. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25^{th} percentile to the 75^{th} percentile. Where the boxes change color shows the median value of the data.

After the initial results were reviewed, the effect that ordered speed of the vehicle had on the ACR was explored and evaluated to determine if it was possible to significantly raise the ACR by increasing vehicle speed. The effect of vehicle speed verses sensor performance was unknown, and it was assumed that there would be no degradation in sensor performance at the increased travel speed. Because the main portion of the modeling concerned a vehicle traveling at 1.64 y/s, with a 2.5 knot current, a baseline simulation was performed to judge how the vehicle traveling at 1.64 y/s with no current would perform. Once complete, the current was returned to the same value and direction the base model used. This value was 2.5 knot current at 10˚. The ordered speed was increased from 1.64 y/s,which is 2.9122 knots, to 3 knots. The simulation was also performed at speeds of 4 knots, 5 knots and 6 knots.

Figure 103, Figure 104, and Figure 105 show the results of increasing the search speed on the alternative architectures. Figure 103 shows for Alternative One, the number of undetected mines are not affected by the search speed; however, the ACR at 3 knots is lower than the higher speed values. The results show if the ordered speed is too close to the speed of the current, the ACR suffers. They also show that once the problem of the current is overcome by increasing speed, the amount of time to perform the detect and classify functions starts to override any improvement caused by an increase in speed.

Figure 104 shows the ordered speed does not have any significant affect on the ACR for Alternative Two. This is probably due to the large detect and classify time. It was concluded it did not matter how fast or slow the vehicle moved through the minefield, and speed does not change the ACR. In general, to improve the ACR a reduction in the time to detect and classify is required.

Figure 105 shows there is a slight improvement as speed goes up for Alternative Three. Since Alternative Three's search is recorded and the data must be downloaded before PMA is started, the amount of time to get through the minefield has an increased influence.

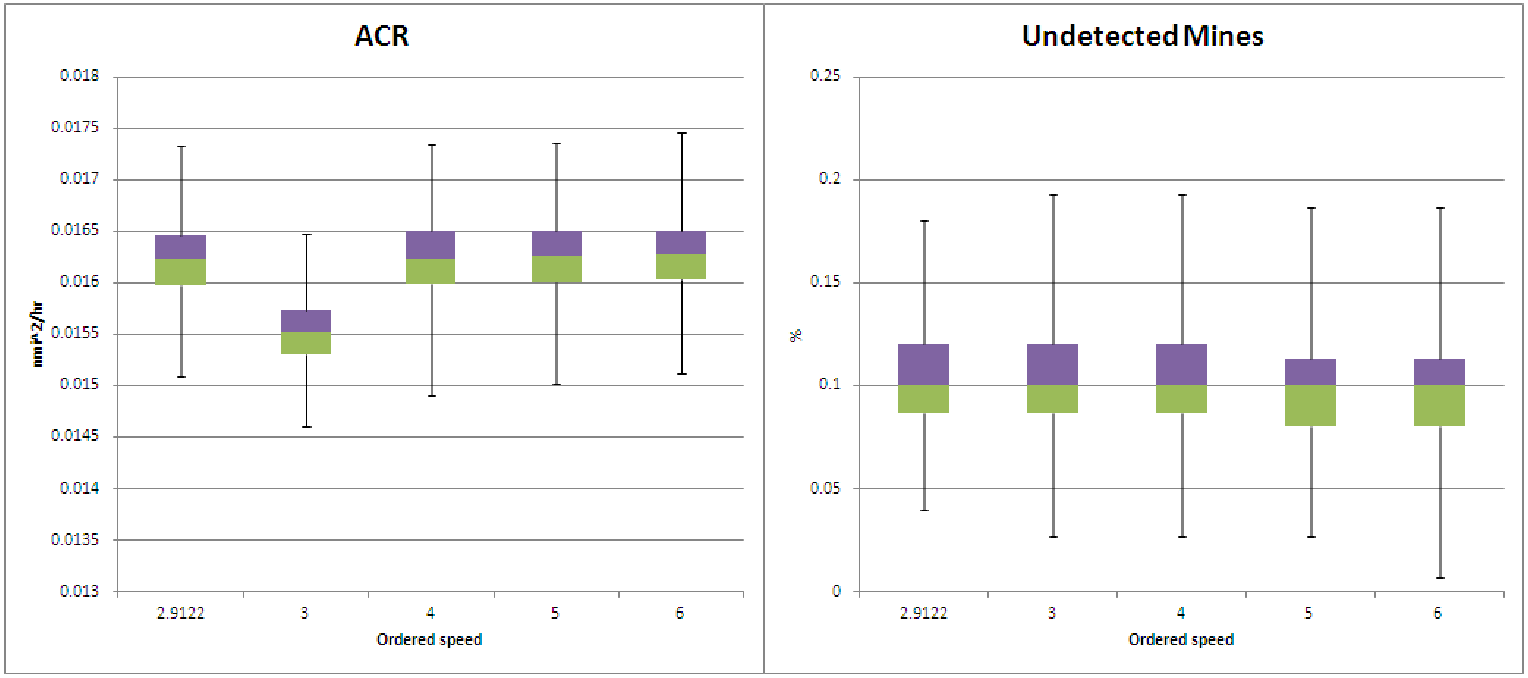

Figure 103. Speed Sensitivity for Alternative One

This figure shows the results from the sensitivity modeling for Architecture One. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

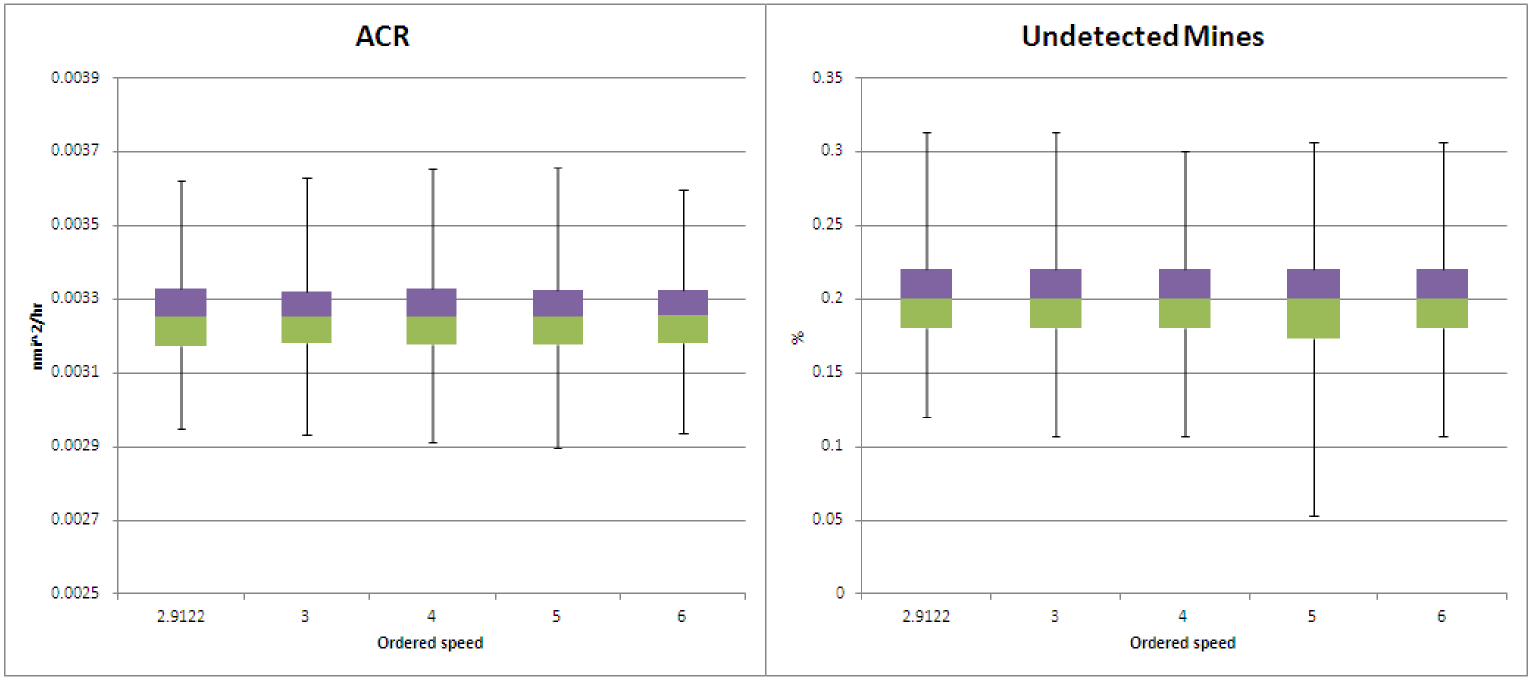

Figure 104. Speed Sensitivity for Alternative Two

This figure shows the results from the sensitivity modeling for Alternative Two. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

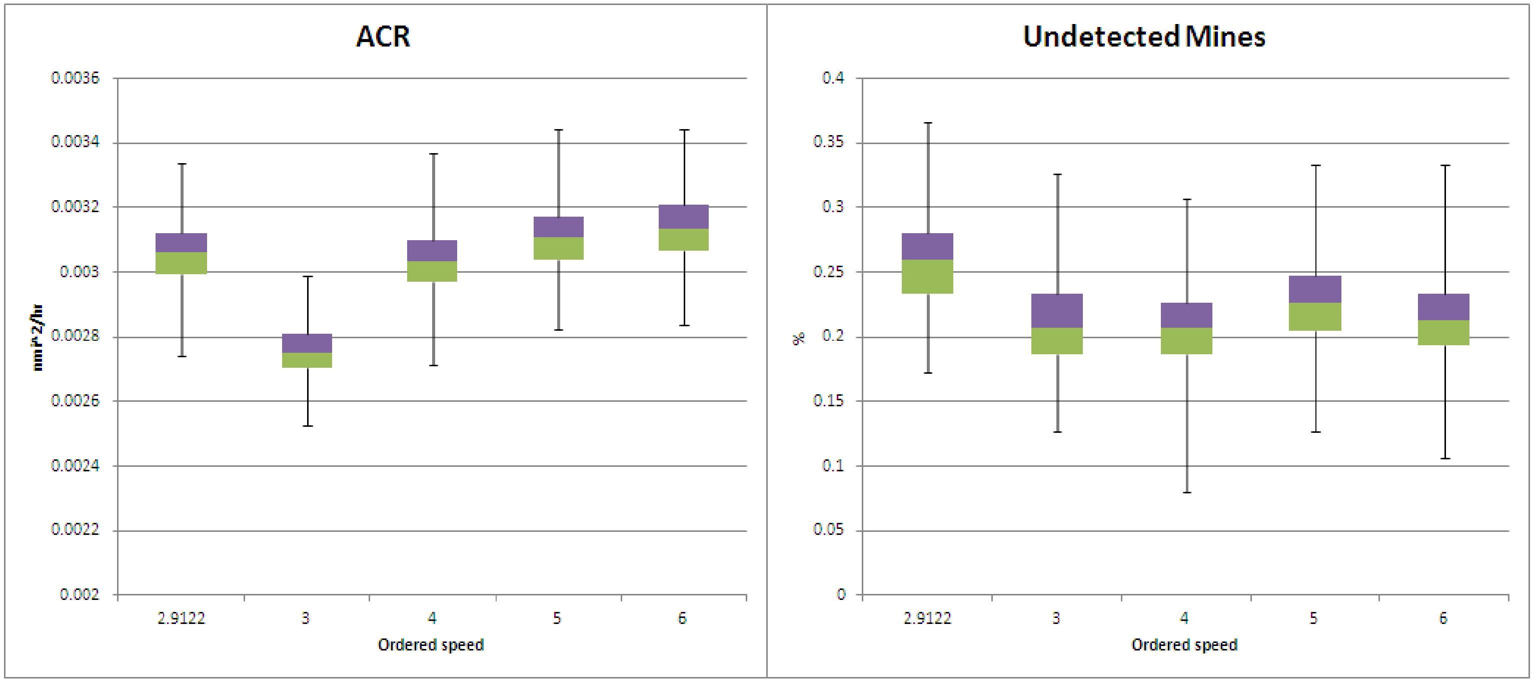

Figure 105. Speed Sensitivity for Alternative Three

This figure shows the results from the sensitivity modeling for Alternative Three. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

The sensitivity analysis was continued by reviewing the affect the time to detect and classify had on the ACR. As can be seen with the analysis performed on the ordered speed of the vehicle the time to detect and classify had the most significant effect on the ACR. This analysis was performed by selecting 3 mean times and 3 standard deviations to use in combination. The first mean time that was selected was time used for Alternative One, which was 60 s. This time was then doubled resulting in the second time of 120 s, which was doubled to give the final time of 240 s. This process was repeated for the standard deviations. The standard deviations were selected as 20 s, 40 s, and 80 s. This resulted in 9 combinations for each alternative which produced a total of 27 combinations. 1000 simulation runs were performed for each combination. The results for Alternative One can be seen in Figure an increase in the standard deviation causes the box plot of the ACR to become wider. This means that if two alternatives are close in the mean time to detect and classify, there will be less chance the two alternatives would be statistically different. The results also show that as the mean time is doubled, the ACR is reduced by less than half the value. As the mean time to detect and classify gets larger the affect approaches half. This is due to the models keeping the time to navigate the minefield constant in this analysis. As the time to detect and classify increases the affect of the time to navigate becomes less significant.

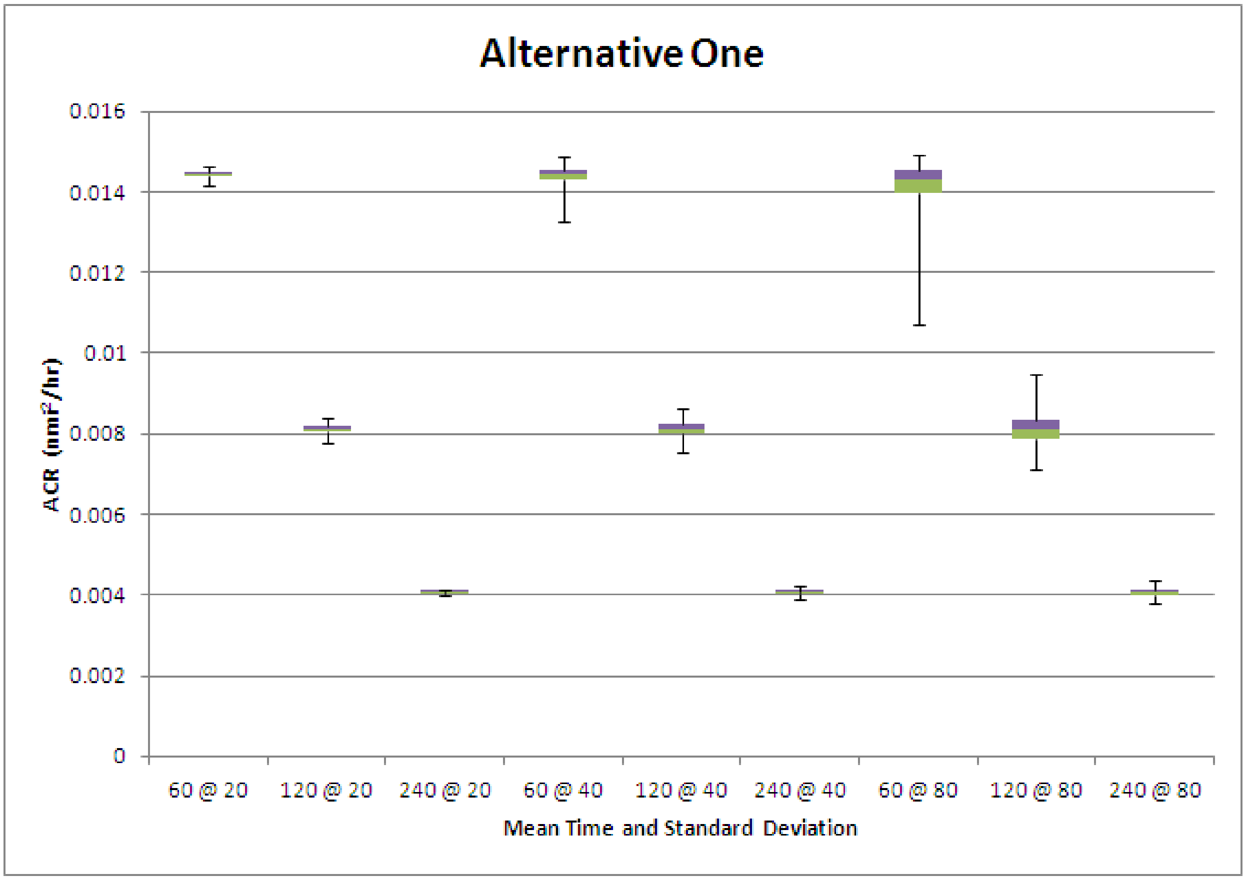

Figure 106. Alternative One: Time to Detect and Classify Sensitivity

This figure shows the results from performing a sensitivity analysis of the time to detect and classify. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

The results for Alternative Two and Three showed the models behaved in a similar fashion. The results for Alternative Two can be seen in Figure 107, and the results for Alternative Three can be seen in Figure 108.

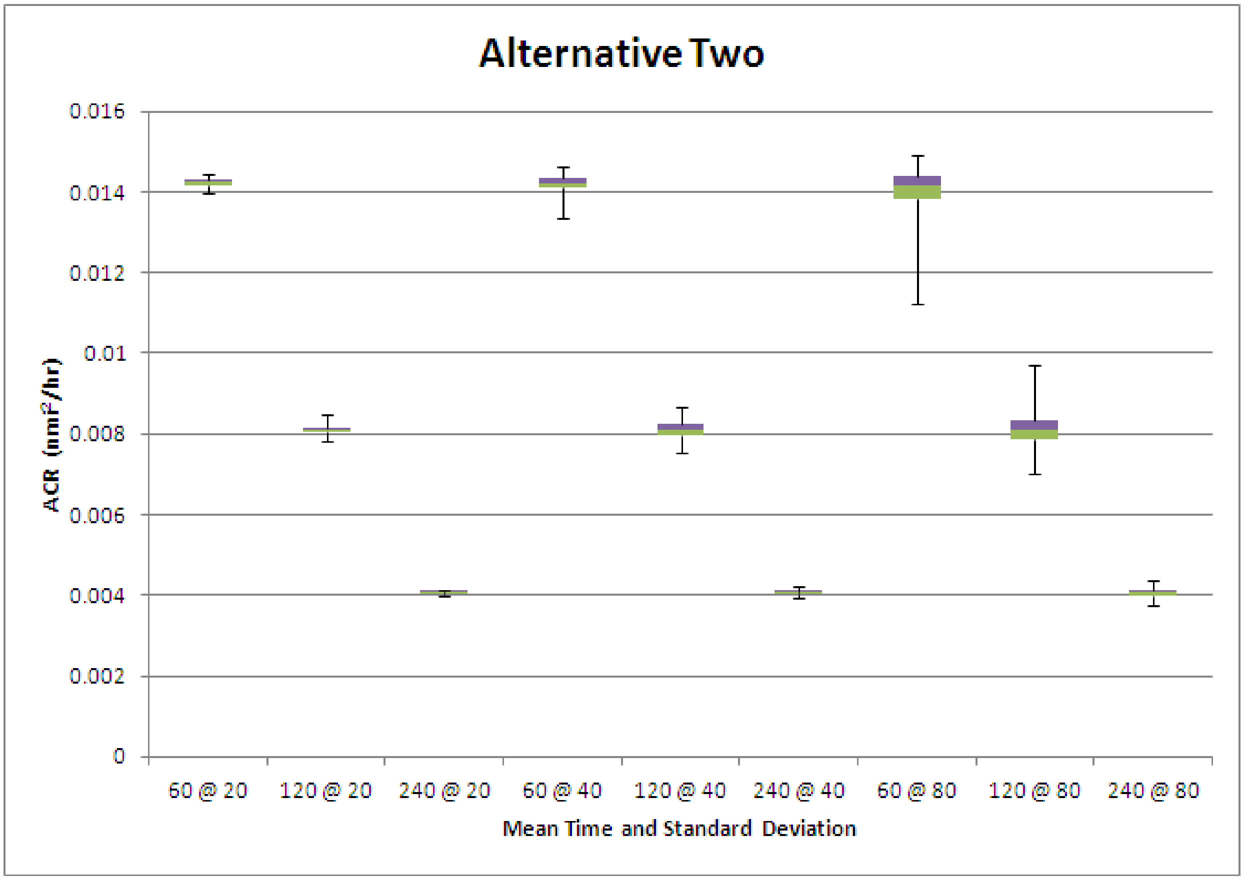

Figure 107. Alternative Two: Time to Detect and Classify Sensitivity

This figure shows the results from performing a sensitivity analysis of the time to detect and classify. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

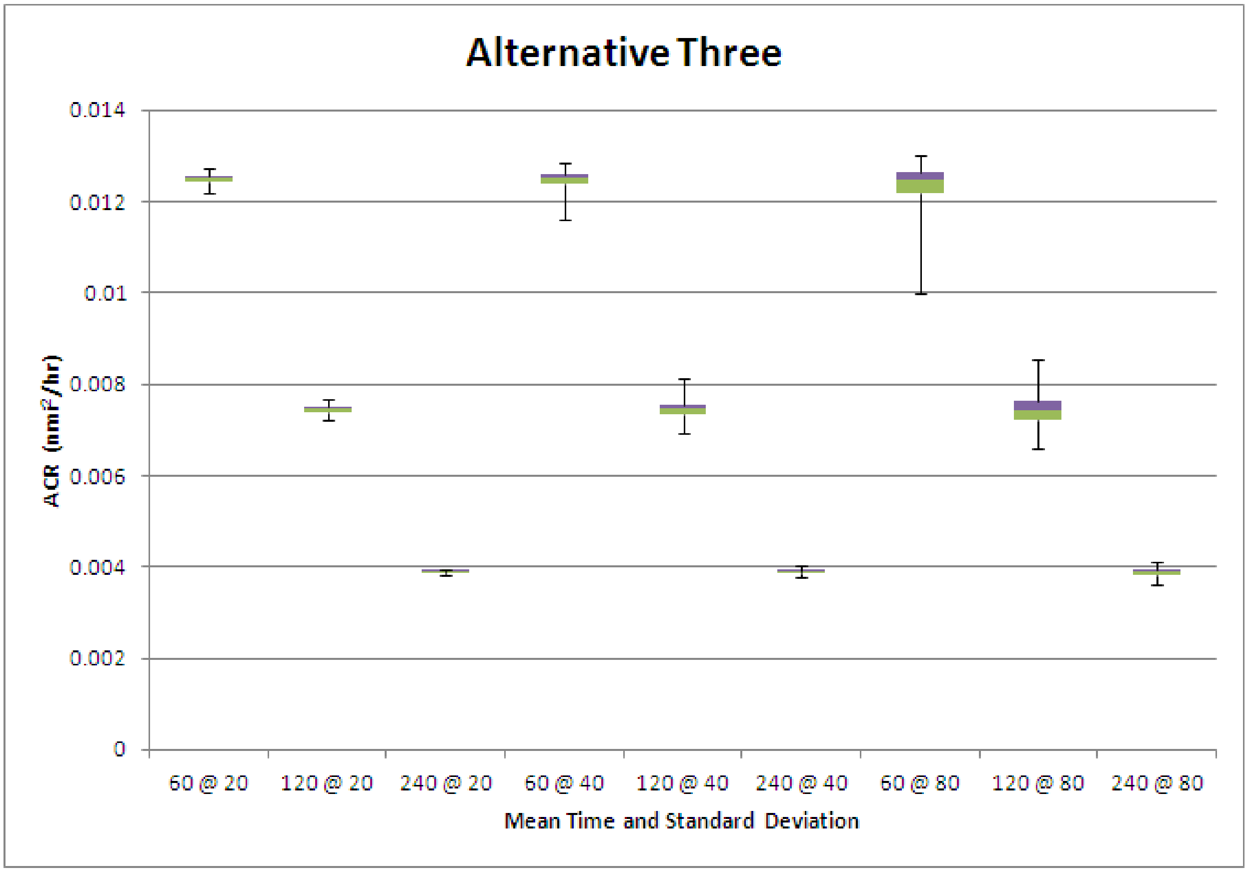

Figure 108. Alternative Three: Time to Detect and Classify Sensitivity

This figure shows the results from performing a sensitivity analysis of the time to detect and classify. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

In order to see how each of the alternatives compared to each other, the results were also graphed at each mean time to detect and classify. It was discovered that with a mean of 60 s with a standard deviation of 20 s, the ACR for all alternatives was statistically different. As either the standard deviation or the mean time was increased, the ACR for Alternative One and Alternative Two became statistically similar using the same mean and standard deviation. For all combinations of means and standard deviations, Alternative Three had a lower ACR. Figure 109 shows the results for the mean time set at 60 s. This shows that only at the 20 s standard deviation Alternative One and Two are significantly different. As the standard deviation increases this significance is reduced.

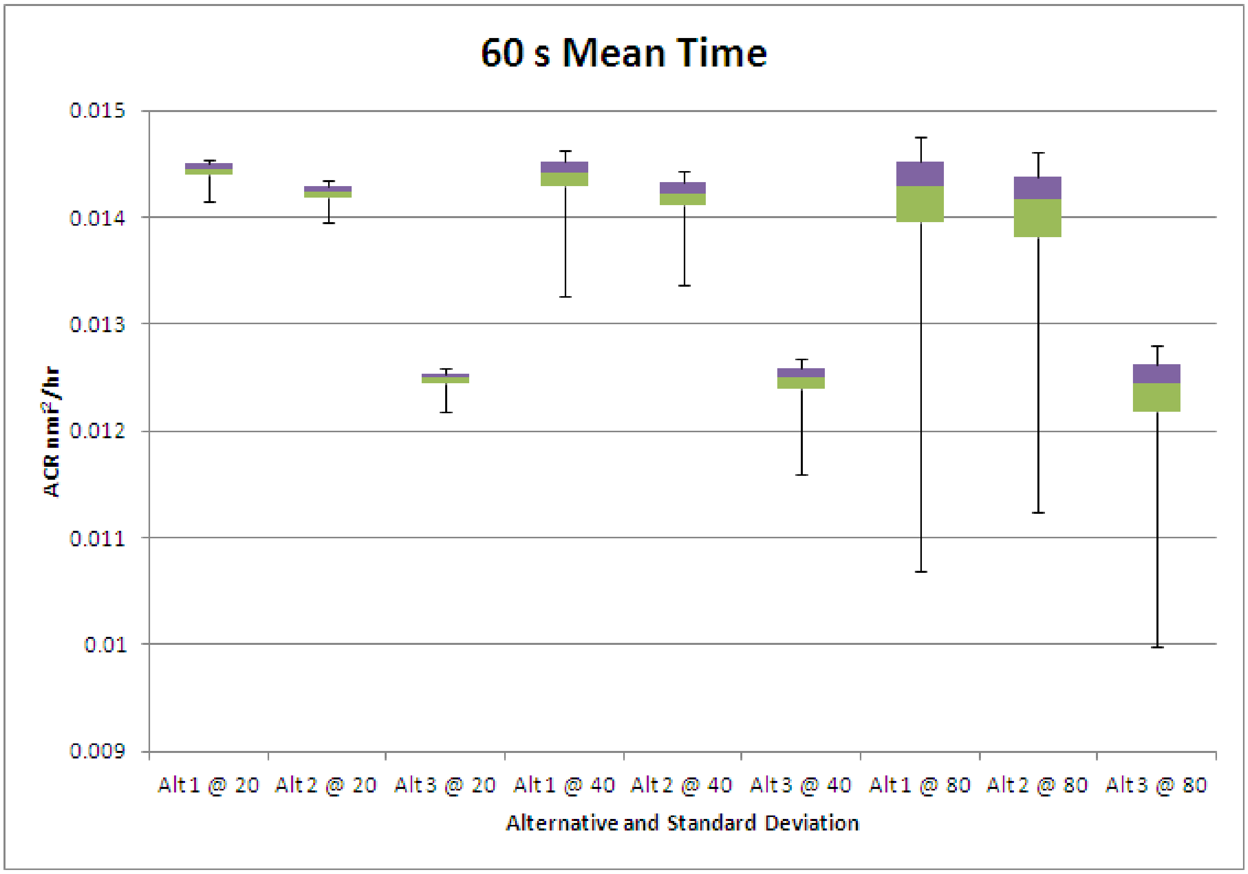

Figure 109. 60 s Mean Time to Detect and Classify sensitivity

This figure shows the performance of the alternatives when the mean time to detect and classify is set to 60 seconds. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

Figure 110 continues to show that as the mean time is increased to 120 s, Alternative One and Two are almost identical. This trend can also be seen in Figure 111 for the 240 s mean time. This trend can be explained because the functions of detect and classify are performed during the mission rather than after the system is recovered. If the mean times were identical then the ACR would become identical; however, the effects of communicating with the SPUDS over the horizon would increase. The reason Alternative Three has a lower ACR is due to the need for the vehicle to be recovered before the data can be analyzed.

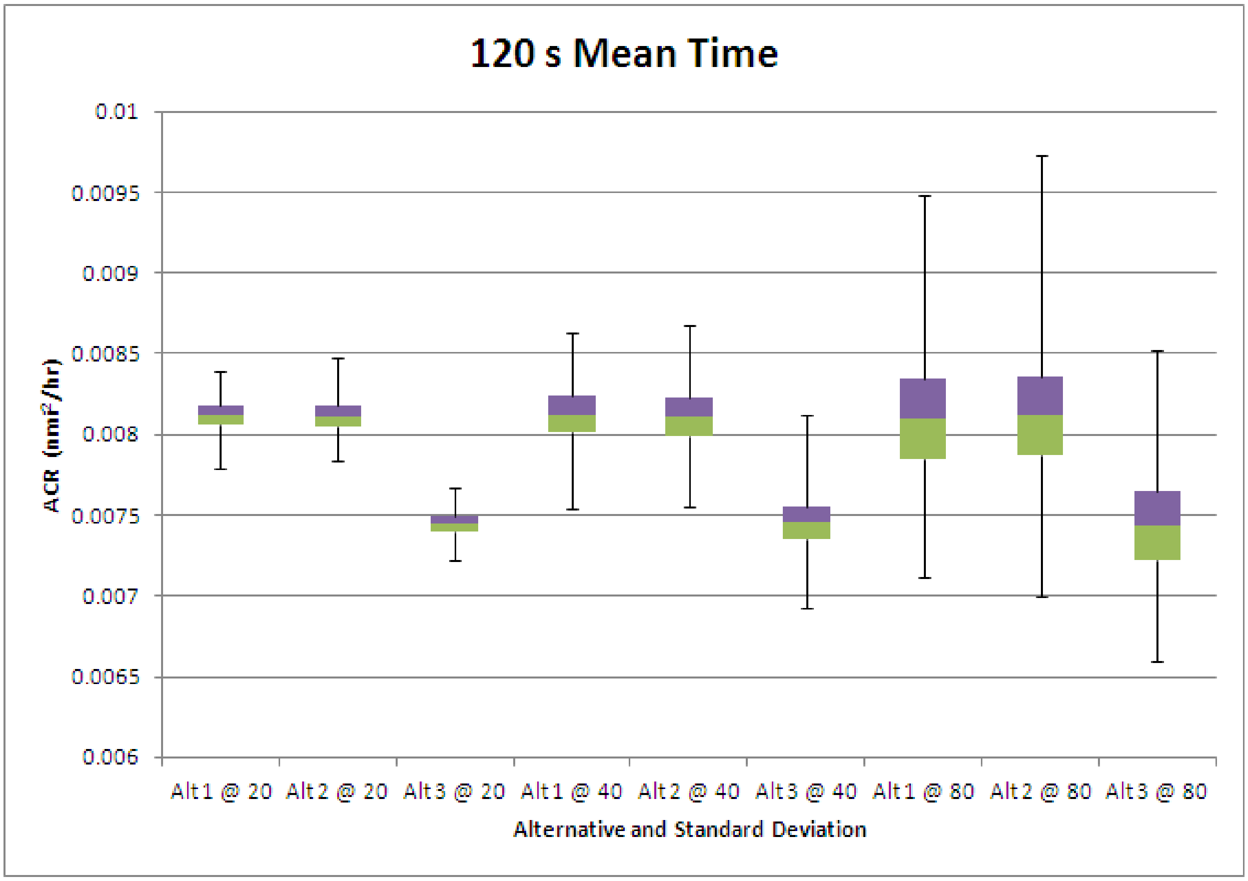

Figure 110. 120 s Mean Time to Detect and Classify sensitivity

This figure shows the performance of the alternatives when the mean time to detect and classify is set to 120 seconds. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

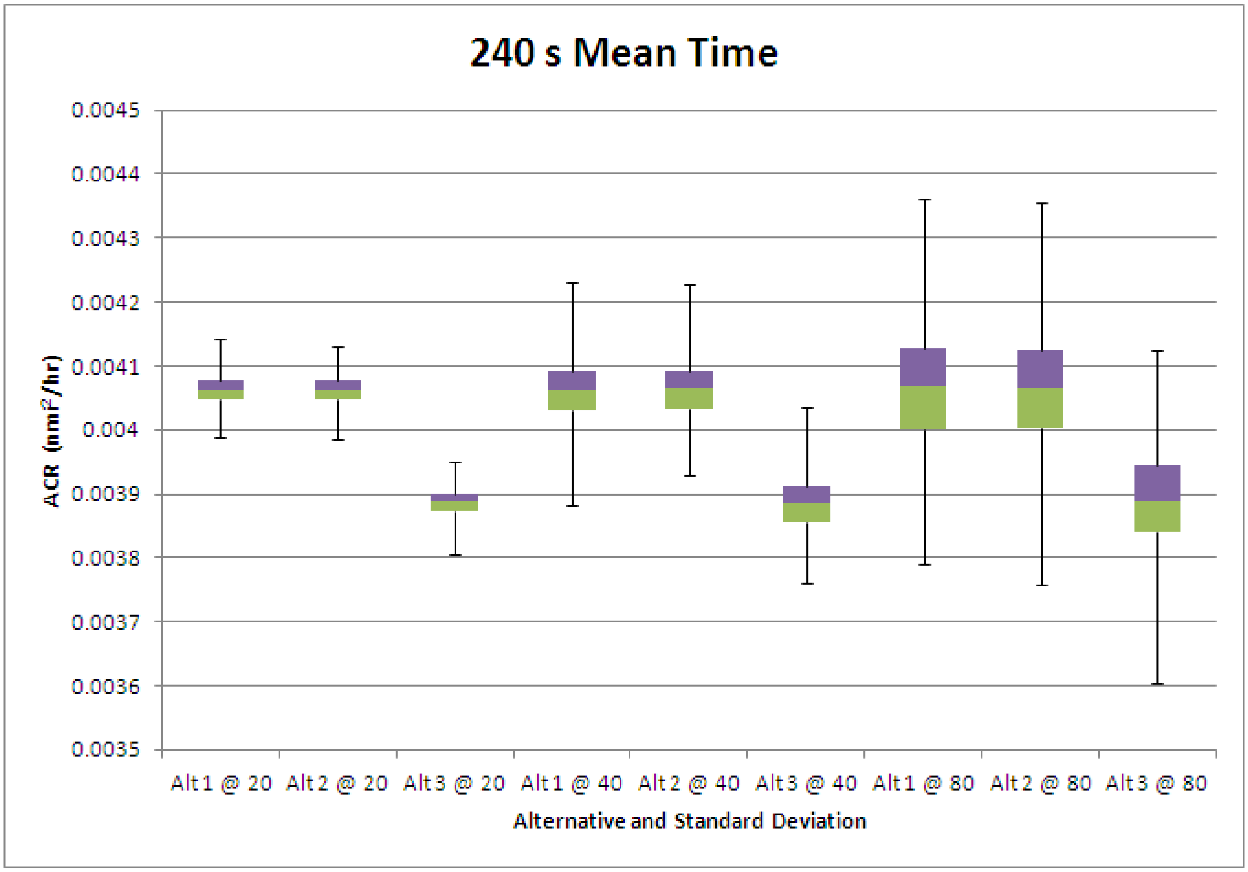

Figure 111. 240 s Mean Time to Detect and Classify sensitivity

This figure shows the performance of the alternatives when the mean time to detect and classify is set to 240 seconds. The error bars on the box plots show the minimum and the maximum values calculated; the boxes themselves cover the 25th percentile to the 75th percentile. Where the boxes change color shows the median value of the data.

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APPENDIX G: ALTERNATIVE COST BREAKDOWNS

A. ALTERNATIVE ONE COST BREAKDOWN STRUCTURE

Figure 112 illustrates the cost breakdown structure for the R&D phase shown at the 3rd level for Alternative One.

CBS	ALTERNATIVE ONE				GRAND TOTAL ($K)			$100,448
1	R&D	Types	Costs ($K) FY-1	Costs ($K) FY-2	Costs ($K) FY-3	Costs ($K) FY-4	Total Cost($K) FY(1-4)	R&D Total Costs ($K)
	4 YRS							
1.1	System/Production Life-Cycle MGT		$250	$260	$649	$675	$1,834	
1.1.1		Project MGT (@ $200K per man year/per year)	$200	$208	$216	$225	$849	
1.1.2		Production MGT (@ $200K per man year/per year)	$0	$0	$216	$225	$441	
1.1.3		Logistics Support MGT (@ $200K per man year/per year)	$50	$52	$216	$225	$543	
1.2	Product Planning		$50	$52	$54	$56	$212	
1.3	Product Research		$400	$156	$162	$168	$886	
1.3.1		Applied Research (@ $200K per man year/per year)	$200	$52	$54	$56	$362	
1.3.2		Research Laboratories (@ $200K per man year/per year)	$200	$104	$108	$112	$524	
1.4	Engineering Design		$600	$5,703	$11,128	$5,948	$23,379	
1.4.1		Systems Engineering (@ $200K per man year/per year)	$200	$208	$216	$225	$849	
1.4.2		Conceptual Design (@ $200K per man year/per year)	$400	$416	$0	$0	$816	$39,490
1.4.3		Preliminary Design (@ $200K per man year/per year)	$0	$416	$433	$0	$849	
1.4.4		Detailed Design (@ $200K per man year/per year)	$0	$0	$433	$450	$883	
1.4.5		Design Support (@ $200K per man year/per year)	$0	$0	$433	$450	$883	
1.4.6		Design Review (@ $200K per man year/per year)	$0	$208	$216	$450	$874	
1.4.7		Software Engineering (@ $200K per man year/per year)	$0	$4,455	$9,397	$4,373	$18,226	
1.5	Design Documentation		$0	$260	$270	$337	$868	
1.5.1		Technical Data Package (@ $100K per man year/per year)	$0	$208	$216	$225	$649	
1.5.2		Technical Manuals (@ $100K per man year/per year)	$0	$52	$54	$112	$219	
1.6	System T&E		$0	$0	$5,580	$6,731	$12,311	
1.6		Validation/Verification(@ $200K per man year/per year)	$0	$0	$0	$422	$422	
1.6.1		Functional Testing (@ $200K per man year/per year)	$0	$0	$0	$506	$506	
1.6.2		Material	$0	$0	$3,417	$3,553	$6,970	
1.6.3		Build Labor	$0	$0	$2,163	$2,250	$4,413	

Figure 112. Alternative One R&D Phase Cost Breakdown Structure

CBS for MCM Alternative One. Costs (shown in $K) for R&D phase are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

Figure 113 illustrates the cost breakdown structure for the Acquisition/Production/Construction phase shown at the 3rd level for Alternative One.

2	Acquisition/Production/ Construction	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	Investment Total Costs ($K)
	5 YRS		FY-5	FY-6	FY-7	FY (8-9)	FY(5-9)	
2.1	Industrial Engineering & Operations Analysis		$1,755	$1,825	$1,898	$4,027	**$9,504**	
2.1.1		Plant Engineering	$351	$365	$380	$805	$1,901	
2.1.2		Manufacturing Engineering	$351	$365	$380	$805	$1,901	
2.1.3		Methods Engineering	$351	$365	$380	$805	$1,901	
2.1.4		Production Control	$351	$365	$380	$805	$1,901	
2.1.5		Sustaining Engineering	$351	$365	$380	$805	$1,901	
2.2	Manufacturing		$2,798	$2,137	$2,573	$4,385	**$11,892**	
2.2.1		Tooling/Test Equipment	$1,170	$608	$253	$67	$2,098	
2.2.2		Fabrication	$585	$365	$253	$134	$1,337	
2.2.3		Material	$686	$714	$1,485	$3,150	$6,034	
2.2.4		Subassembly/Assembly	$117	$243	$380	$671	$1,411	
2.2.5		Inspection & Test	$117	$122	$127	$268	$634	
2.2.6		Packing & Shipping	$6	$12	$25	$67	$110	
2.2.7		Manufacturing Rework	$117	$73	$51	$27	$267	
2.3	Construction		$526	$547	$569	$1,208	**$2,851**	
2.3.1		Manufacturing Facilities (@ $20/sqft/yr x 10,000 sqft)	$234	$243	$253	$537	$1,267	$26,042
2.3.2		Test Facilities (@ $10/sqft/yr x 5,000 sqft)	$58	$61	$63	$134	$317	
2.3.3		Consumer Operational Facilities (@ $10/sqft/yr x 5,000 sqft)	$58	$61	$63	$134	$317	
2.3.4		Maintenance Facilities (@ $10/sqft/yr x 5,000 sqft)	$58	$61	$63	$134	$317	
2.3.5		Training Facilities (@ $10sqft/yr x 5,000 sqft)	$58	$61	$63	$134	$317	
2.3.6		Inventory Warehouse (@ $10/sqft/yr x 5,000 sqft)	$58	$61	$63	$134	$317	
2.4	Quality Control		$117	$243	$127	$268	**$755**	
2.4.1		Inspection & Test	$117	$243	$127	$268	$755	
2.5	Initial Logistics Support		$263	$182	$190	$403	**$1,038**	
2.5.1		Test & Support Equipment	$146	$61	$63	$134	$405	
2.5.2		Transportation & Handling	$29	$30	$32	$67	$158	
2.5.3		Technical Data	$29	$30	$32	$67	$158	
2.5.4		Personnel & Training	$29	$30	$32	$67	$158	
2.5.5		Training & Equipment	$29	$30	$32	$67	$158	

Figure 113. Alternative One Acquisition/Production/Construction Cost Breakdown

CBS for MCM Alternative One. Costs (shown in $K) for Acquisition/Production/Construction are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

Figure 114 illustrates the cost breakdown structure for the Operating & Support and Disposal phases shown at the 3rd level for Alternative One.

3	Operating & Support	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	O&S Total Costs ($K)
	8 YRS		FY(10-11)	FY(12-13)	FY(14-15)	FY(16-17)	FY(10-17)	
3.1	System/Product Operations		$1,336	$1,343	$1,417	$1,490	**$5,586**	
3.1.1		Operating Personnel (@ $100K per man year/per year)	$581	$584	$616	$648	$2,429	
3.1.2		Operator Training (@ $5K/operator/yr)	$29	$29	$31	$32	$121	
3.1.3		Operational Facilities (@ $10/sqft/yr x 5,000 sqft)	$145	$146	$154	$162	$607	
3.1.4		System Maintainer	$581	$584	$616	$648	$2,429	
3.2	Sustaining Logistics Support (ISEA)		$5,751	$4,784	$5,458	$8,995	**$24,988**	**$30,574**
3.2.1		Warehouse Facilities (@ $10/sqft/yr x 5,000 sqft)	$145	$146	$154	$162	$607	
3.2.2		Maintenance Facilities & Training Facilities (@ $10/sqft/yr x 5,000 sqft)	$145	$146	$154	$162	$607	
3.2.3		Maintenance Personnel Training (@ $12.5K/yr)	$73	$73	$77	$81	$304	
3.2.4		Test & Support Equipment	$181	$73	$77	$162	$493	
3.2.5		System/Product Modifications	$290	$292	$308	$324	$1,214	
3.2.6		System Maintenance	$87	$88	$92	$97	$364	
3.2.7		Spares (Spare parts(critical-5% or less) and systems(no more than 10%))	$4,829	$3,966	$4,595	$8,007	$21,398	
4	Disposal	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	Disposal Total Costs ($K)
	4 YRS		FY-18	FY-19	FY-20	FY-21	FY(18-21)	
			$1,023	$1,064	$1,106	$1,150	**$4,343**	
4.1		Logistics Support Requirements (@ $200K per man year/per year)	$390	$405	$421	$438	$1,654	
4.2		Personnel Support (@ $200K per man year/per year)	$390	$405	$421	$438	$1,654	**$4,343**
4.3		Equipment Support	$97	$101	$105	$110	$414	
4.4		Transportation & handling support	$49	$51	$53	$55	$207	
4.5		Facilities & data (@ $10/sqft/yr x 5,000 sqft)	$97	$101	$105	$110	$414	

Figure 114. Alternative One O&S and Disposal Phases Cost Breakdown Structure

CBS for MCM Alternative One. Costs (shown in $K) for O&S and Disposal phases are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

B. ALTERNATIVE TWO COST BREAKDOWN STRUCTURE

Figure 115 illustrates the cost breakdown structure for the R&D phase shown at the 3rd level for Alternative Two.

CBS	ALTERNATIVE TWO						GRAND TOTAL ($K)	$285,076
1	R&D	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	R&D Total Costs ($K)
	4 YRS		FY-1	FY-2	FY-3	FY-4	FY(1-4)	
1.1	System/Production Life-Cycle MGT		$250	$260	$649	$675	$1,834	
1.1.1		Project MGT (@ $200K per man year/per year)	$200	$208	$216	$225	$849	
1.1.2		Production MGT (@ $200K per man year/per year)	$0	$0	$216	$225	$441	
1.1.3		Logistics Support MGT (@ $200K per man year/per year)	$50	$52	$216	$225	$543	
1.2	Product Planning		$50	$52	$54	$56	$212	
1.2.1		Program Planning (@ $200K per man year/per year)	$50	$52	$54	$56	$212	
1.3	Product Research		$400	$156	$162	$168	$886	
1.3.1		Applied Research (@ $200K per man year/per year)	$200	$52	$54	$56	$362	
1.3.2		Research Laboratories (@ $200K per man year/per year)	$200	$104	$108	$112	$524	
1.4	Engineering Design		$600	$2,733	$4,863	$3,033	$11,229	
1.4.1		Systems Engineering (@ $200K per man year/per year)	$200	$208	$216	$225	$849	
1.4.2		Conceptual Design (@ $200K per man year/per year)	$400	$416	$0	$0	$816	$24,957
1.4.3		Preliminary Design (@ $200K per man year/per year)	$0	$416	$433	$0	$849	
1.4.4		Detailed Design (@ $200K per man year/per year)	$0	$0	$433	$450	$883	
1.4.5		Design Support (@ $200K per man year/per year)	$0	$0	$433	$450	$883	
1.4.6		Design Review (@ $200K per man year/per year)	$0	$208	$216	$450	$874	
1.4.7		Software Engineering (@ $200K per man year/per year)	$0	$1,485	$3,132	$1,458	$6,075	
1.5	Design Documentation		$0	$260	$270	$337	$868	
1.5.1		Technical Data Package (@ $100K per man year/per year)	$0	$208	$216	$225	$649	
1.5.2		Technical Manuals (@ $100K per man year/per year)	$0	$52	$54	$112	$219	
1.6	System T&E		$0	$0	$4,715	$5,213	$9,928	
1.6		Validation/Verification(@ $200K per man year/per year)	$0	$0	$0	$141	$141	
1.6.1		Functional Testing (@ $200K per man year/per year)	$0	$0	$0	$169	$169	
1.6.2		Material	$0	$0	$2,552	$2,654	$5,206	
1.6.3		Build Labor	$0	$0	$2,163	$2,250	$4,413	

Figure 115. Alternative Two R&D Phase Cost Breakdown Structure

CBS for MCM Alternative Two. Costs (shown in $K) for R&D phase are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

Figure 116 illustrates the cost breakdown structure for the Acquisition/Production/Construction phase shown at the 3rd level for Alternative Two.

2	Acquisition/Production/ Construction	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	Investment Total Costs ($K)
	5 YRS		FY-5	FY-6	FY-7	FY (8-9)	FY(5-9)	
2.1	Industrial Engineering & Operations Analysis		$1,170	$1,217	$1,265	$2,685	$6,336	
2.1.1		Plant Engineering	$234	$243	$253	$537	$1,267	
2.1.2		Manufacturing Engineering	$234	$243	$253	$537	$1,267	
2.1.3		Methods Engineering	$234	$243	$253	$537	$1,267	
2.1.4		Production Control	$234	$243	$253	$537	$1,267	
2.1.5		Sustaining Engineering	$234	$243	$253	$537	$1,267	
2.2	Manufacturing		$8,152	$6,383	$6,279	$10,585	$31,399	
2.2.1		Tooling/Test Equipment	$1,170	$608	$253	$67	$2,098	
2.2.2		Fabrication	$2,340	$1,460	$1,012	$537	$5,349	
2.2.3		Material	$2,513	$2,028	$2,179	$4,773	$11,493	
2.2.4		Subassembly/Assembly	$468	$973	$1,518	$2,685	$5,644	
2.2.5		Inspection & Test	$1,170	$973	$1,012	$2,148	$5,303	
2.2.6		Packing & Shipping	$23	$49	$101	$268	$442	
2.2.7		Manufacturing Rework	$468	$292	$202	$107	$1,070	
2.3	Construction		$1,053	$1,095	$1,139	$2,008	$5,295	
2.3.1		Manufacturing Facilities (@ $20/sqft/yr x 20,000 sqft)	$468	$487	$506	$800	$2,261	$50,204
2.3.2		Test Facilities (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$134	$499	
2.3.3		Consumer Operational Facilities (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.3.4		Maintenance Facilities (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.3.5		Training Facilities (@ $10sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.3.6		Inventory Warehouse (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.4	Quality Control		$468	$973	$506	$1,074	$3,021	
2.4.1		Inspection & Test	$468	$973	$506	$1,074	$3,021	
2.5	Initial Logistics Support		$1,053	$730	$759	$1,611	$4,153	
2.5.1		Test & Support Equipment	$585	$243	$253	$537	$1,618	
2.5.2		Transportation & Handling	$117	$122	$127	$268	$634	
2.5.3		Technical Data	$117	$122	$127	$268	$634	
2.5.4		Personnel & Training	$117	$122	$127	$268	$634	
2.5.5		Training & Equipment	$117	$122	$127	$268	$634	

Figure 116. Alternative Two Acquisition/Production/Construction Cost Breakdown

CBS for MCM Alternative Two. Costs (shown in $K) for Acquisition/Production/Construction are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

Figure 117 illustrates the cost breakdown structure for the Operating & Support and Disposal phases shown at the 3rd level for Alternative Two.

3	Operating & Support	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	O&S Total Costs ($K)
	8 YRS		FY(10-11)	FY(12-13)	FY(14-15)	FY(16-17)	FY(10-17)	
3.1	System/Product Operations		$30,052	$32,504	$35,156	$38,025	$135,737	
3.1.1		Operating Personnel (@ $100K per man year/per year)	$26,132	$28,264	$30,571	$33,065	$118,032	
3.1.2		Operator Training (@ $5K/operator/yr)	$1,307	$1,413	$1,529	$1,653	$5,902	
3.1.3		Operational Facilities (@ $10/sqft/yr x 10,000 sqft)	$290	$314	$340	$367	$1,311	
3.1.4		System Maintainer	$2,323	$2,512	$2,717	$2,939	$10,492	
3.2	Sustaining Logistics Support (ISEA)		$16,914	$14,885	$14,196	$22,806	$68,801	$204,538
3.2.1		Warehouse Facilities (@ $10/sqft/yr x 10,000 sqft)	$290	$314	$340	$367	$1,311	
3.2.2		Maintenance Facilities & Training Facilities (@ $10/sqft/yr x 10,000 sqft)	$290	$314	$340	$367	$1,311	
3.2.3		Maintenance Personnel Training (@ $12.5K/yr)	$290	$314	$340	$367	$1,311	
3.2.4		Test & Support Equipment	$181	$79	$85	$184	$529	
3.2.5		System/Product Modifications	$1,161	$1,256	$1,359	$1,470	$5,246	
3.2.6		System Maintenance	$348	$377	$408	$441	$1,574	
3.2.7		Spares (Spare parts(critical-5% or less) and systems(no more than 10%))	$14,351	$12,231	$11,326	$19,610	$57,518	
4	Disposal	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	Disposal Total Costs ($K)
	4 YRS		FY-18	FY-19	FY-20	FY-21	FY(18-21)	
			$1,266	$1,317	$1,369	$1,424	$5,377	
4.1		Logistics Support Requirements (@ $200K per man year/per year)	$390	$405	$421	$438	$1,654	
4.2		Personnel Support (@ $200K per man year/per year)	$390	$405	$421	$438	$1,654	$5,377
4.3		Equipment Support	$97	$101	$105	$110	$414	
4.4		Transportation & handling support	$195	$203	$211	$219	$827	
4.5		Facilities & data (@ $10/sqft/yr x 10,000 sqft)	$195	$203	$211	$219	$827	

Figure 117. Alternative Two O&S and Disposal Phases Cost Breakdown Structure

CBS for MCM Alternative Two. Costs (shown in $K) for Acquisition/Production/Construction are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

C. ALTERNATIVE THREE COST BREAKDOWN STRUCTURE

Figure 118 illustrates the cost breakdown structure for the R&D phase shown at the 3rd level for Alternative Three.

CBS	ALTERNATIVE THREE					GRAND TOTAL ($K)		$326,328
1	R&D	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	R&D Total Costs ($K)
	4 YRS		FY-1	FY-2	FY-3	FY-4	FY(1-4)	
1.1	System/Production Life-Cycle MGT		$250	$260	$649	$675	$1,834	
1.1.1		Project MGT (@ $200K per man year/per year)	$200	$208	$216	$225	$849	
1.1.2		Production MGT (@ $200K per man year/per year)	$0	$0	$216	$225	$441	
1.1.3		Logistics Support MGT (@ $200K per man year/per year)	$50	$52	$216	$225	$543	
1.2	Product Planning		$50	$52	$54	$56	$212	
1.2.1		Program Planning (@ $200K per man year/per year)	$50	$52	$54	$56	$212	
1.3	Product Research		$400	$156	$162	$168	$886	
1.3.1		Applied Research (@ $200K per man year/per year)	$200	$52	$54	$56	$362	
1.3.2		Research Laboratories (@ $200K per man year/per year)	$200	$104	$108	$112	$524	
1.4	Engineering Design		$600	$2,733	$4,863	$3,033	$11,229	
1.4.1		Systems Engineering (@ $200K per man year/per year)	$200	$208	$216	$225	$849	
1.4.2		Conceptual Design (@ $200K per man year/per year)	$400	$416	$0	$0	$816	$23,973
1.4.3		Preliminary Design (@ $200K per man year/per year)	$0	$416	$433	$0	$849	
1.4.4		Detailed Design (@ $200K per man year/per year)	$0	$0	$433	$450	$883	
1.4.5		Design Support (@ $200K per man year/per year)	$0	$0	$433	$450	$883	
1.4.6		Design Review (@ $200K per man year/per year)	$0	$208	$216	$450	$874	
1.4.7		Software Engineering (@ $200K per man year/per year)	$0	$1,485	$3,132	$1,458	$6,075	
1.5	Design Documentation		$0	$260	$270	$337	$868	
1.5.1		Technical Data Package (@ $100K per man year/per year)	$0	$208	$216	$225	$649	
1.5.2		Technical Manuals (@ $100K per man year/per year)	$0	$52	$54	$112	$219	
1.6	System T&E		$0	$0	$4,233	$4,711	$8,944	
1.6		Validation/Verification(@ $200K per man year/per year)	$0	$0	$0	$141	$141	
1.6.1		Functional Testing (@ $200K per man year/per year)	$0	$0	$0	$169	$169	
1.6.2		Material	$0	$0	$1,529	$1,590	$3,119	
1.6.3		Build Labor	$0	$0	$2,704	$2,812	$5,516	

Figure 118. Alternative Three R&D Phase Cost Breakdown Structure

CBS for MCM Alternative Three. Costs (shown in $K) for R&D phase are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

Figure 119 illustrates the cost breakdown structure for the Acquisition/Production/Construction phase shown at the 3rd level for Alternative Three.

2	Acquisition/Production/ Construction	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	Investment Total Costs ($K)
	5 YRS		FY-5	FY-6	FY-7	FY (8-9)	FY(5-9)	
2.1	Industrial Engineering & Operations Analysis		$1,170	$1,217	$1,265	$2,685	**$6,336**	
2.1.1		Plant Engineering	$234	$243	$253	$537	$1,267	
2.1.2		Manufacturing Engineering	$234	$243	$253	$537	$1,267	
2.1.3		Methods Engineering	$234	$243	$253	$537	$1,267	
2.1.4		Production Control	$234	$243	$253	$537	$1,267	
2.1.5		Sustaining Engineering	$234	$243	$253	$537	$1,267	
2.2	Manufacturing		$6,411	$5,384	$5,142	$5,734	**$22,671**	
2.2.1		Tooling/Test Equipment	$1,160	$600	$248	$65	$2,073	
2.2.2		Fabrication	$2,320	$1,440	$992	$520	$5,272	
2.2.3		Material	$820	$848	$876	$905	$3,449	
2.2.4		Subassembly/Assembly	$464	$960	$1,488	$2,600	$5,512	
2.2.5		Inspection & Test	$1,160	$1,200	$1,240	$1,280	$4,880	
2.2.6		Packing & Shipping	$23	$48	$99	$260	$430	
2.2.7		Manufacturing Rework	$464	$288	$198	$104	$1,054	
2.3	Construction		$1,053	$1,095	$1,139	$2,008	**$5,295**	
2.3.1		Manufacturing Facilities (@ $20/sqft/yr x 10,000 sqft)	$468	$487	$506	$800	$2,261	**$41,476**
2.3.2		Test Facilities (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$134	$499	
2.3.3		Consumer Operational Facilities (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.3.4		Maintenance Facilities (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.3.5		Training Facilities (@ $10sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.3.6		Inventory Warehouse (@ $10/sqft/yr x 10,000 sqft)	$117	$122	$127	$268	$634	
2.4	Quality Control		$468	$973	$506	$1,074	**$3,021**	
2.4.1		Inspection & Test	$468	$973	$506	$1,074	$3,021	
2.5	Initial Logistics Support		$1,053	$730	$759	$1,611	**$4,153**	
2.5.1		Test & Support Equipment	$585	$243	$253	$537	$1,618	
2.5.2		Transportation & Handling	$117	$122	$127	$268	$634	
2.5.3		Technical Data	$117	$122	$127	$268	$634	
2.5.4		Personnel & Training	$117	$122	$127	$268	$634	
2.5.5		Training & Equipment	$117	$122	$127	$268	$634	

Figure 119. Alternative Three Acquisition/Production/Construction Breakdown

CBS for MCM Alternative Three. Costs (shown in $K) for Acquisition/Production/Construction are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

Figure 120 illustrates the cost breakdown structure for the Operating & Support and Disposal phases shown at the 3rd level for Alternative Three.

3	Operating & Support	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	O&S Total Costs ($K)
	8 YRS		FY(10-11)	FY(12-13)	FY(14-15)	FY(16-17)	FY(10-17)	
3.1	System/Product Operations		$41,753	$45,160	$48,845	$52,831	**$201,704**	
3.1.1		Operating Personnel (@ $100K per man year/per year)	$39,488	$42,711	$46,196	$49,965	$178,360	
3.1.2		Operator Training (@ $5K/operator/yr)	$1,974	$2,136	$2,310	$2,498	$8,918	
3.1.3		Operational Facilities (@ $10/sqft/yr x 10,000 sqft)	$290	$314	$340	$367	$1,311	
3.1.4		System Maintainer	$2,904	$3,140	$3,397	$3,674	$13,115	
3.2	Sustaining Logistics Support (ISEA)		$13,916	$13,171	$12,247	$14,465	**$53,798**	**$255,503**
3.2.1		Warehouse Facilities (@ $10/sqft/yr x 10,000 sqft)	$290	$314	$340	$367	$1,311	
3.2.2		Maintenance Facilities & Training Facilities (@ $10/sqft/yr x 10,000 sqft)	$290	$314	$340	$367	$1,311	
3.2.3		Maintenance Personnel Training (@ $12.5K/yr)	$363	$393	$425	$459	$1,639	
3.2.4		Test & Support Equipment	$181	$79	$85	$184	$529	
3.2.5		System/Product Modifications	$1,161	$1,256	$1,359	$1,470	$5,246	
3.2.6		System Maintenance	$348	$377	$408	$441	$1,574	
3.2.7		Spares (Spare parts(critical-5% or less) and systems(no more than 10%))	$11,281	$10,438	$9,292	$11,177	$42,188	
4	Disposal	Types	Costs ($K)	Costs ($K)	Costs ($K)	Costs ($K)	Total Cost($K)	Disposal Total Costs ($K)
	4 YRS		FY-18	FY-19	FY-20	FY-21	FY(18-21)	
			$1,266	$1,317	$1,369	$1,424	**$5,377**	
4.1		Logistics Support Requirements (@ $200K per man year/per year)	$390	$405	$421	$438	$1,654	
4.2		Personnel Support (@ $200K per man year/per year)	$390	$405	$421	$438	$1,654	**$5,377**
4.3		Equipment Support	$97	$101	$105	$110	$414	
4.4		Transportation & handling support	$195	$203	$211	$219	$827	
4.5		Facilities & data (@ $10/sqft/yr x 10,000 sqft)	$195	$203	$211	$219	$827	

Figure 120. Alternative Three O&S and Disposal Phases Cost Breakdown

CBS for MCM Alternative Three. Costs (shown in $K) for O&S and Disposal phases are broken down to the third level and totaled for respective fiscal years and overall phase of the program. Likewise, total cost for each phase is provided.

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APPENDIX H: DEFINITIONS

Table 60 provides further explanation for terms used throughout the report.

Table 60. Definitions List

Table lists key terms that require definition to assist in the understanding.

Advance Task Force	A temporary organization which precedes the main body to the objective area, for preparing the objective for the main assault by conducting such operations as reconnaissance, seizure of supporting positions, mine countermeasures, preliminary bombardment, underwater demolitions, and air support.
Amphibious Assault	Amphibious assault is the principal type of amphibious operation that involves establishing a force on a hostile or potentially hostile shore. Only amphibious assault involves the permanence of establishing a LF ashore. The special measures required for a rapid build-up of combat power ashore, from an initial zero capability, creates organizational and technical differences between amphibious operations and land warfare.
Amphibious Force	An amphibious force is a naval force and Landing Force, together with supporting forces that are trained, organized and equipped for amphibious operations. In naval usage, it is the administrative type command of a fleet (i.e., national amphibious capability.
Amphibious Task Force (ATF)	An ATF is the task organization formed for the purpose of conducting an amphibious operation. An ATF always includes navy forces and a Landing Force (LF), with their organic aviation and supporting forces.
Area Coverage Rate	Area of concern searched by a single vehicle divided by the time to achieve 100% coverage of the objective area by the search sensor suite. This parameter applies to open water areas in non-complex environments where the system can operate in parallel tracks at optimum speed for sensors employed, unencumbered by obstacles (e.g. piers, pilings, other man-made structures, complex bottom types, etc.). In the diverse configurations and environments characteristic

	of coastal areas (e.g. pier/berthing areas, etc.), irregular search patterns and tactics may be required to achieve Pd/Pc and Pi performance against characteristic threat objects. Characterization of ACR for different environments is desirable; however these are performance measures for tactical employment of the system. ACR may require tradeoff in the more complex environments and confined areas; hence, a system level threshold value for ACR for all possible environments is not appropriate.
Area Of Operation	An operational area defined by the joint force commander for land and maritime forces that should be large enough to accomplish their missions and protect their forces.
Biomimetic Sonar	It is adaptive mobile sonar normally located on a robot arm that moves in response to the echo time of flights to position an object along the transmitter axis at a known range and elevation to maximize the incident acoustic energy. The system employs a learning stage followed by a recognition stage.
Boat lane	A lane for amphibious assault landing craft, which extends seaward from the landing beaches to the line of departure. The width of a boat lane is determined by the length of the corresponding beach. The current typical length is from 2000 to 2700 yards. The width is 500 yards.
Clandestine Operations	It is an intelligence or military operation carried out in such a way that the operation goes unnoticed.
Classify	A term used to indicate the MCM vehicle has classified the mine contact as a bottom mine, moored mine, or drifting mine. The detected contact is further investigated, usually with a higher resolution sonar, and classified as a (Mine Like Contact) MILC or (None Mine Object) NOMBO.
Detect	A term used to indicate the Mine Counter Measure Vehicle detects a mine-like object. The object may or may not be a mine.
False Alarm Rate	The False alarm rate is the number of times the MCM vehicle incorrectly detects and classifies a "Non-Mine-Like Object". It is defined by: (Number of Non-Mine-like objects detected /Number on non-mine-like opportunities) X

	(Number of non-mine-like objects incorrectly classified/number of non-mine-like objects detected).
Fully Autonomous	This is a mode of operation of an unmanned system (UMS) wherein the UMS is expected to accomplish its mission, within a defined scope, without human intervention. Note that a team of UMSs may be fully autonomous while the individual team members may not be due to the needs to coordinate during the execution of team missions.
HRI	Human-robot interactions are the human robot interfaces and interactions.
Identify	Identify is a term used to indicate the MCM vehicle identifies the mine-like contact as a mine or not a mine. Identification should be made using an optical system so that a positive ID of the mine can be made. This prevents expenditure of neutralization efforts and charges on nonthreatening objects. It also keeps the MCM forces from assuming.
Landing Force (LF)	A LF is the task organization of ground units assigned to an amphibious operation, which may include aviation and/or surface units when assigned to Commander Landing Force (CLF).
Line of Sight (LOS)	Refers to electro-magnetic radiation or acoustic wave propagation. Electromagnetic transmission includes light emissions traveling in a straight line. The rays or waves may be diffracted, refracted, reflected, or absorbed by atmosphere and obstructions with material and generally cannot travel OTH or behind obstacles.
Littoral Penetration Points	An LPP is a point within an LPS where the actual transition from waterborne/over-water movement (“feet wet”) to overland (“feet dry”) movement occurs.
Littoral Penetration Site	An LPS is a continuous segment of coastline through which landing forces cross by surface or vertical means.
Locate	Locate is a term to indicate the MCM vehicle has determine/processed and stored the location of the mine or mine-like contact to be used for future processing. The contact position is refined and plotted as precisely as possible (specifying navigation sensor, datum, and position

	in latitude/longitude to a thousandth of a minute) so that further prosecution can be carried out either immediately or at a later time. MCM forces use the WGS-84 datum as measured by GPS P-code as the standard reference system.
Neutralization	The mine is either rendered inoperative or removed from the area.
NOMBO	Non-Mine Bottom Object is an object on the bottom of the water that appears to be a mine. However, it is a Non-Mine.
Over-The-Horizon (OTH)	At is an amphibious operation initiated from beyond visual and radar range of the enemy shore.
Reacquire	Reacquire is the act of a MCM vehicle finding a mine again after it has gone off to perform another mission such as search.
Remote Control	A mode of operation of a Unmanned system (UMS) wherein the human operator, without benefit of video or other sensory feedback, directly controls the actuators of the UMS on a continuous basis, from off the vehicle and via a tethered or radio linked control device using visual line-of sight cues. In this mode, the UMS takes no initiative and relies on continuous or nearly continuous input from the user.
Sea State	It is the general condition of the free surface on a large body of water with respect to wind waves and swells. A sea state is characterized by statistics, including the wave height, period, and power spectrum.
Semi-Autonomous	A mode of operation of an Unmanned system (UMS) wherein the human operator and/or the UMS plan(s) and conduct(s) a mission that requires various levels of human-robot interaction (HRI).
Supervisor	A supervisor is an agent that has supervisory control over a subordinate agent(s); it will intermittently reprogram its subordinates, using information that it has gathered from the environment or taken from the subordinate agents. As for all agents, a supervisor can be human or artificial, without restriction.
Supervisory Control	The notion of supervisory control is as follows: supervisory control is where one or more operators are intermittently

	programming and receiving information from an artificial intelligent agent.
Tele-operation	A mode of operation of a Unmanned system (UMS) wherein the human operator, using video feedback and/or other sensory feedback, either directly controls the actuators or assigns incremental goals, waypoints in mobility situations, on a continuous basis, from off the vehicle and via a tethered or radio linked control device. In this mode, the UMS may take limited initiative in reaching the assigned incremental goals.
UXO	Unexploded explosive ordnance – is an explosive ordnance that has been primed, fused, armed, or otherwise prepared for action, that has been fired, dropped, launched, projected, or placed in such a manner as to constitute a hazard to operations, installations, personnel, or material and remains unexploded either by malfunction or design or for any other cause. Sensor systems related to these munitions have the capability to detect, identify, and select specific targets using infrared, proximity, magnetic influence, acoustic, and seismic technologies which can be encountered on land or sea. Attempts to approach and perform a render-safe procedure on these munitions may cause detonation of the devices.

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LIST OF SYMBOLS, ACRONYMS, AND ABBREVIATIONS

AAV	Amphibious Assault Vehicles
ACR	Area Coverage Rate
AGS	Advanced Gun System
ALMDS	Airborne Laser Mine Detection System
AMCM	Airborne Mine Counter Measures
AMNS	Airborne Mine Neutralization System
AO	Area of Operation
ASCM	Anti-Ship Cruise Missile
ASROC	Anti-Submarine Rocket
ATF	Advance Task Force
ATR	Automatic Target Recognition
AUV	Autonomous Underwater Vehicle
BIT	Built in Test
BOE	Back-of-the-Envelope
BULS	Bottom Unmanned Underwater Vehicle Localization System
BZ	Beach Zone
C2	Command and Control
C4I	Command, Control, Communications, Computers, and Intelligence
CAS	Close Air Support
CARSTRKGRU	Carrier Strike Group
CG	Commanding General
CV	Carrier
COBRA	Coastal Battlefield Reconnaissance and Analysis
CONOPS	Concept of Operations
CMCO	Countermine Counter-Obstacle
CMS	Countermine Systems
CRD	Consolidated Requirements Document
DESRON	Destroyer Squadron
DET	Detachment
DDG	Destroyer
DRM	Design Reference Mission
DVIS	Diver Visual Information System
DTE	Detect to Engage
EA	Electronic Attack
EFFBD	Enhanced Functional Flow Body Diagram
EFV	Expeditionary Fighting Vehicle

EM	Electromagnetic
EMI	Electromagnetic Impulse
EODMU	Explosive Ordnance Disposal Mobil Unit
EOD	Explosive Ordinance Disposal
EUNS	Expeditions Underwater Neutralization System
FFG	Fast Frigate
FLS/DLS	Forward Looking Sonar / Down Looking Sonar
FSW	Feet of Sea Water
I-IPT	Interoperability Integrated Product Team
JABS	Joint Assault Breaching System
JDAM	Joint Direct Attack Munition
JHSV	Joint High Speed Vessel
KTs	Knots
LCAC	Landing Craft Air Cushion
LCC	Amphibious Command Ship
LCM/LCU	Landing Craft Mechanized and Utility
LCS	Littoral Combat Ship
LHA	Amphibious Assault Ship
LIDAR	Light Detection and Ranging System
LPP	Littoral Penetration Point
LPD	Amphibious Transport Dock
LSD	Landing Ship Dock
LST	Landing Ship Tank
MCM	Mine Countermeasures
MCCDC	Marine Corps Combat Development Command
MEB	Marine Expeditionary Brigade
MK	Mark
MLP	Mobile Landing Platform
MMS	Marine Mammals System
MODS	Mine Obstacle Defeat System (MODS)
MOE	Measure of Effectiveness
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NATO	North Atlantic Treaty Organization
NGFS	Naval Gun Fire System
NGS	Naval Gun Support
NMMP	Navy Marine Mammal Program

NOMBO	Non-Mine Bottom Objects
NPS	Naval Postgraduate School
OAMCM	Organic Airborne Mine Countermeasure
OASIS	Organic Airborne and Surface Influence Sweep
ONR	Office of Naval Research
OTH	Over The Horizon
PMA	Post Mission Analysis
PMS	Project Management Ship
RAMICS	Rapid Airborne Mine Clearance System
RPA	Remote Pilot Aircraft
RPV	Remote Pilot Vehicle
SMCM	Surface Mine Counter Measures
SoS	System of Systems
SS	Sea State
SSC	Ship to Shore Connector
STIL	Streak Tube Imaging Laser
STOM	Ship to Objective Movement
SZ	Shallow Zone
TA	Target Acquisition
TASM	Tomahawk Anti-Ship Missile
TBD	To Be Determined
TLAM	Tomahawk Land Attack Missile
TMD	Tactical Munition Dispenser
TOC	Total Ownership Costs
TPED	Tasking, Processing, Exploitation, And Distribution
UBA	Underwater Breathing Apparatus
UIS	Underwater Imaging System
UMCM	Underwater Mine Countermeasures
UMS	Unmanned system
UUV	Unmanned Underwater Vehicle
UV	Underwater Vehicle
UXO	Unexploded Ordnance
VSW	Very Shallow Water
VTUAV	Vertical Takeoff Unmanned Air Vehicle
WSESRB	Weapon System Explosive Safety Review Board
WWII	World War II
XO	Executive Officer

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